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Mobile Electric Power Technologies for the Army of the Future

Engines, Power Source, and Electrical Aspects

Prepared by the
Committee on Mobile Electric
Power Plant Technologies
Energy Engineering Board
Commission on Engineering and Technical Systems
National Research Council

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PREFACE

The U.S. Army's need for mobility prompted its interest in this study of engine, direct energy conversion, and electrical technologies that would increase the power per unit mass and volume (PMV) for mobile electric power (MEP) units. Increased PMV will give the troops in the front lines more mobility and will allow quicker movement of troop units by air since high PMV will make MEP units more air transportable.

The Army asked the National Research Council (NRC) to assess current and projected developments in mobile electric power generation technologies. Through the Energy Engineering Board, the NRC appointed the Committee on Mobile Electric Power (MEP) Plant Technologies to undertake an assessment of these technologies and to recommend R & D strategies in order to ensure the development and fielding of cost-effective mobile electric power plants that meet Army requirements for the period from 1990 to 2015. (See Appendix A for the committee's Statement of Task).

The committee held a number of meetings in the United States with a variety of groups having information of interest. This included visits to a number of U.S. and foreign companies and inviting representatives of other companies to committee meetings (See Appendix B for site visits, a list of people who attended committee meetings and the committee's itinerary). The technical literature was also surveyed extensively by the committee members. The committee was accorded outstanding cooperation in conducting its studies from all the groups and persons contacted and gratefully acknowledges their assistance; this report would have been incomplete without their help and information.

James Zucchetto, Senior Program Officer, provided detailed guidance and assistance in the many aspects of arranging visits and meetings, and in preparing the report from drafts submitted by the committee. He also drafted parts of the report. The report would not have been completed without his able assistance. A small report writing task force from the committee made up of Phil Myers, Tom Jahns, Jim Zucchetto and John Johnson met several times to edit and revise the report. The report would not have been as clear and as concise without the effort of this group. Drusilla Barnes had the essential job of deciphering and transforming individual contributions into the report's final form. We acknowledge the contribution she made to the report.

I would like to thank the members of the committee for their contributions of time and knowledge to the report. This report represents their professional knowledge refined by the information gathered in the literature and from the various government-industry data presented to the committee. It was a difficult task to cover both engine, other energy conversion devices, and electrical technologies and to integrate this knowledge into an evaluation of future MEP units. We had many spirited discussions and all members gave freely of their time and technical opinions. This effort is greatly appreciated.

John H. Johnson
Chairman
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Power Plant Technologies

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LIST OF ABBREVIATIONS AND ACRONYMS

AC	Alternating current
AMG	AM General
AMTEC	Alkali metal thermoelectric converter
APU	Auxiliary Power Units
BOI	Basis of issue
CGSA	Commercial Generator Sets and Assemblies
CSD	Constant-speed drive
CUCV	Commercial Utility Cargo Vehicle
dB	Decibel
DC	Direct current
DoD	U.S. Department of Defense
ECM	Electronic countermeasures
EEC	European Economic Community
EM	Electromagnetic
ESPL	Equivalent Sound Pressure Level
ev	Electron volt
FLIR	Forward-looking infrared
FY	Fiscal year
GAME	Generator Acquisition Management Execution
GM	General Motors
GTO	Gate turn off thyristor
HAEMP	High altitude electromagnetic pulse
HMMWV	High Mobility Multipurpose Wheeled Vehicle

HVDC	High-voltage direct current
IC	Integrated circuit
ICE	Internal combustion engine
IGBT	Insulated-gate bipolar transistors
IR	Infrared
LCC	Life-cycle cost
MCFC	Molten carbonate fuel cell
MCT	MOS-controlled thyristors
MEP	Mobile Electric Power
MIL-STD	Military standard
MTI	Mechanical Technology Incorporated
MOPP	Mission oriented protective posture
MOS	Metal oxide semiconductor
MOSFETS	MOS field-effect transistors
MPSPU	Turbomach Multipurpose Small Power Unit
MTBF	Mean time between failure
NASP	National Aerospace plane
NATO	North Atlantic Treaty Organization
NdFeB	Neodymium-iron-boron
NDI	Non-development item
OCV	Open circuit potential
PAFC	Phosphoric acid fuel cell
PM	Permanent magnet
PMV	Power per unit mass and volume
PTO	Power take off

R & D	Research and Development
SADI	Spark-assisted direct injection
SCR	Silicon controlled rectifier
SDI	Strategic Defense Initiative
SHP	Shaft horsepower
SI	Spark ignited
SmCo	Samarium-cobalt
SOFC	Solid oxide fuel cell
SPE	Sulfonic-acid polymer
SPL	Sound pressure level
SR	Switched reluctance
SSDED	Signature-suppressed Diesel Engine Drive
STE	Standard test equipment
TARGET	Team to Advance Research in Gas Energy Conversion
TCCS	Texaco Controlled Combustion System
UPS	Uninterruptible power supply
USS	United Stirling of Sweden
VED	Vehicle engine driven
VSCF	Variable-speed constant frequency

EXECUTIVE SUMMARY

The Committee on Mobile Electric Power (MEP) Plant Technologies considered the state of the art of MEP units (usually called generator sets, a generic term including engine-generators, fuel cells, batteries and thermal-to-electric devices) in the commercial sector as well as technologies that may mature during the period from 1990 to 2015. Based on its technology assessment, coupled with a consideration of the Army fuels policy and the projected battlefield needs in the twenty-first century, the committee recommends research and development (R & D) strategies for the U.S. Army's Logistics Support Directorate at Ft. Belvoir that can lead to the fielding of cost-effective MEP units meeting Army requirements.

POLICY CONSIDERATIONS

The Army currently maintains a fleet of about 133,000 MEP units, ranging in power from about 1.5 to 750 kW. Most units are less than 10 kW in size, gasoline-powered, and more than 10 yrs old. However, the Army policy of "A Single Fuel on the Battlefield", adopted in 1986, requires the use of the jet fuel, JP-8, for both aircraft and ground equipment. A new Army procurement program will increase the number of diesel-powered generator sets (that can also use JP-8 fuel) by the mid-1990s but will not provide the high-performance MEP units the committee judges essential to the mission of the future Army.

In the longer term, the warfare concept for the twenty-first century (referred to as Army 21) envisions a battlefield employing combat systems possessing ranges, lethality, and detection capabilities far surpassing everything known in contemporary warfare. Army 21 conflicts will be intense, of short duration, and require highly mobile sources of electric power. Although not considered by the committee, small, lightweight, and low-signature generator sets are also probably important attributes for conflicts with terrorists or armies less technically developed than the U.S. Army.

Low noise requirements are important for satisfying community requirements during peacetime operation. However, to minimize detection, future high-performance MEP sets operating near the front lines or on the battlefield must have extremely low noise, infrared, and electromagnetic signatures that are not available on existing Army or commercial units. These units should also satisfy Army needs for power quality, high mobility (i.e., have high power per unit mass and volume [PMV]), design standardization, high reliability, acceptable cost, long life, supportability, and acceptable fuel efficiency. Achieving these demanding signature requirements will probably require enclosures and active noise suppression. Providing low signature MEP that satisfies these high-performance requirements is critical to the Army 21 concept.

The present menu of Army generator sets, including the new procurement, does not have units that will have the high-performance characteristics needed for Army 21. Furthermore, the civilian market will not provide small high-performance generator sets, especially ones that are man-portable in size. In the judgment of the committee, the continuation of current procurement practices and development policy of using non-developmental items (NDI; these are commercial items) will not result in any high-performance MEP units that meet the needs of Army 21. Military R & D will be required to realize these high-performance MEP units for different MEP classes as defined below.

As discussed later, there are many electrical system technologies that could be used for Army MEP. Furthermore, the use of the vehicle engine of various utility and tactical vehicles for electric power generation (so-called onboard or vehicle-engine-driven power) can supplement, and in emergency situations replace, MEPs and therefore should be developed.

Hence, the committee reached the following conclusions:

o The supply of electric power for the needs of Army 21 is of critical importance to the mission of the Army.

o Based on the committee's observations, it appears that the Army does not recognize that high-performance mobile electric power is essential to the Army's strategic thinking regarding Army 21. For example, the continuation of current procurement practices and development policy will not result in a fleet of high-performance MEP units that meets the needs of Army 21. High-performance MEP units will require military research and development.

The committee recommends:

o <u>The Army should integrate the needs for mobile electric power supply, as dictated by the Army 21 concept, into its overall strategic planning. This requires that a central authority be established having responsibilities for an overall MEP development plan for defining needs for high-performance MEP and how MEP technologies should be integrated into Army 21.</u>

SYSTEMS PERSPECTIVE

To assess the MEP technology needs of the Army and the ability of commercial developments to satisfy these needs, the committee developed a classification scheme for MEP sets based on their mode of transportation. The two major classes are man-portable and vehicle-portable. Man-portable units can be carried by one soldier (e.g., with some sort of backpack arrangement; this is referred to as personal power) or hand carried some distance by one or two soldiers. Vehicle-portable units include those that can be towed behind a vehicle, carried on a vehicle and offloaded, or incorporated into a vehicle (e.g., an alternator powered by a vehicle engine, referred to as onboard power or vehicle-engine-driven [VED] power).

To meet the needs of Army 21, the committee judges that a systems engineering approach to the supply of electric power from mobile sources can result in significant improvements in mobility and logistics. For example, a typical standard generator set involves an engine and electric alternator directly coupled together. If 60 Hz is a requirement, this configuration limits the maximum engine speed to 3,600 rpm. Since, for a given power level, the combined engine and alternator sizes decrease significantly as speed is increased, significant savings in alternator weight and volume can be achieved by designing the engine and alternator to operate at higher shaft speeds.

However, such increases above 3,600 rpm will require the introduction of power conditioning using power electronics, adding weight and volume components, which must be balanced against the alternator-engine savings.

The additional weight and volume associated with the power conditioner depends heavily on power quality requirements. If present power quality requirements are maintained, it is unlikely that a net savings can be achieved using present technology for rotor speeds below about 6,000 rpm. However, recent advances in power electronics are significantly reducing the weight and volume penalties associated with high-quality power conditioners, inviting periodic reevaluation of this approximate rpm limit.

As mentioned above, system considerations also invite examination of the generator set-load interface to cope with Army 21 demands. In particular, present generator set output power quality requirements embodied in Military Standard (MIL-STD)-1332B are conservatively high, penalizing generator set and power conditioner weight and volume. Since many typical electrical loads do not require this premium power quality (knowing that premium power quality is an Army requirement, the load designer specifies premium power quality regardless of need), there are opportunities for significant net systems weight and volume savings by selectively relaxing key power quality requirements; those specific loads that require high input power quality can provide for their own needs by the addition of appropriate conditioning components in their input stages.

High-performance MEP units required on Army 21 battlefields can also gain in power per unit weight and mass by adoption of a systems approach to the design of the generator set. For example, the generator can be

designed to share the same housing, rotor shaft, bearings, and cooling system with the engine, providing the basis for substantial weight and volume reductions. Such integrated designs for high-performance MEP generator sets will only become available through special development efforts outside the NDI commercial acquisition plans.

There are certainly electrical system opportunities to be incorporated into Army MEP systems. In many circumstances it is useful to connect multiple MEP units together to supply the same load or a combination of loads. Such paralleling is also useful for backup reliability and uninterrupted power during load transfers. A systems perspective strongly suggests that increased use of generator set networks (e.g., cable connections among MEP units and loads) could significantly improve the overall reliability of Army electrical power systems through higher redundancy. Hence, the committee concludes that there are networking capabilities for Army MEP units that can increase both the flexibility and power availability of fielded MEP sets. The committee makes the following recommendations:

- The Army should pursue plans to selectively relax MEP power quality requirements in order to achieve significant MEP mobility improvements by reducing overall system weight and volume.
- Opportunities for reducing the size and weight of high-performance MEP units by increasing shaft speeds above 3600 rpm should be carefully reviewed in light of major advances in power conditioner technology.
- In view of the special requirements for high-performance MEP units, the Army should evaluate the merits of physically integrating the prime mover and alternator of all MEP units intended for combat zone usage.

MOBILE ELECTRIC POWER SYSTEMS

In evaluating the prime mover and electrical technologies for providing MEP to the Army, the committee judges that nuclear power, thermionic, and Nernst effect technologies were not applicable as MEP units for reasons of safety, cost, weight, and power density. Although Stirling engines have been under development for many years and promise quiet, multifuel operation, it does not appear they will be competitive from a development status or cost standpoint.

Man-portable Systems

Personal Power

Personal power units should be of such a size and weight that one soldier can conveniently carry it along with other equipment (e.g., in a backpack arrangement). Currently, there is no satisfactory source of personal power. Small (tens of watts) power requirements could be met by available and future batteries but higher power requirements would require a replaceable fuel source.

Batteries supply limited energy and power and, because they must be replaced, pose a supply problem. Small internal combustion engines can use JP-8 fuel but are noisy and have vibration problems; reducing their signature to acceptably low levels would markedly increase their cost, mass, and volume. Fuel cells have a potentially attractive PMV but require scarce materials, exotic fuels, and are not in quantity production. There is a prototype thermoelectric 100 W device, developed by Teledyne Energy Systems, that uses diesel fuel. Its weight (21 kg with fuel for a 12-h mission) seems somewhat high for a backpack arrangement but future developments might improve its power density.

There were differences in the judgment of the committee as to the relative practicality of small engine-generator sets for man-portable, backpack use. The majority, but not all, of the committee concluded that small engine-generator sets were impractical and that batteries and fuel cells were potential candidates.

In view of the above, the Army should carefully review the requirements for personal power for individual soldiers, specify and balance such needs as power and signature against portability, and weigh the advantages of personal power against the development costs. If this review shows that personal power is cost effective, and if the power required is beyond those power levels that can be supplied by batteries, development funds will be required. For this situation, there were differences of opinion in the committee. A minority judges that less development would be required to modify small internal combustion engines, to reduce noise and allow use of JP-8 fuel than would be necessary to make a personal power, hydrogen fuel cell practical. The majority judge the reverse. There was complete agreement that completion of the recommended review would clarify the optimum solution for man-portable personal power.

Hence, the committee recommends:

- The Army should quantify its performance, size, and use needs for personal man-portable MEP units. If power requirements exceed battery capabilities, the use of fuel cells with disposable hydrogen cartridges are judged to be the most viable potential candidate although high-speed engines or other energy conversion devices may be applicable. Army battery development for personal power should continue at the same level of activity since it is a promising technology for man-portable power if the power needs are small (approximately less than 150 W).

Two-person Portable

The two-person portable units are MEP sets in the range of one to several kilowatts (the upper size depends on technology). They are envisioned by the committee to have high power density and low signature so that two soldiers can carry them over some distance under combat conditions. In this power range, diesel engines with a family concept could meet the Army's requirements. Achieving low signature would require significant R & D or considerable added bulk and weight. Other stratified-charge

engines are not sufficiently well developed and the committee judges that it will be difficult to design a stratified-charge rotary engine of this size.

An attractive approach, which might give higher PMV, is to modify either a reciprocating or rotary spark-ignition engine, such as lowering the compression ratio or modifying the combustion chamber, so that JP-8 fuel can be burned. The fuel economy of these engines would be worse than a diesel engine, and starting with JP-8 would be a problem, but they should be cheaper, lighter, and have lower signature.

Gas turbines in this size range would have the highest PMV, fuel consumption, initial, and life-cycle costs, and are not available on a commercial basis.

The high-performance systems required by Army 21 will require integration of prime mover and alternator, modified power quality requirements, power-conditioning technologies, and special signature reduction, which are unlikely to be commercially available.

Vehicle-Portable Systems

Vehicle-Transportable Units

The vehicle-transportable units vary from a few kilowatts that can be individually unloaded from a vehicle (by hand or mechanical aid) to the larger units of many tens or hundreds of kilowatts that are towed behind vehicles. Up to about 300 kW, the applicable prime movers are the diesel, rotary, gas turbine, and low-compression, spark-ignition engine (JP-8 compatible). The diesel is commercially available and the most developed. For power levels of about 10 or 15 kW and above, the decreased fuel efficiency of a modified spark-ignition engine would be a severe penalty. Below the 30 to 50 kW range, because of high fuel consumption and initial cost, the gas turbine is the least attractive, although its high speed can allow small alternators to be used. For the larger power sizes (30 to 50 kW and above), the best current prime mover is the diesel engine although there are underway both military and commercial developments in the rotary and gas turbine prime mover technologies that could change this situation. Above 300 kW, because of transport reasons, the gas turbine is the most likely MEP candidate. Thus, considering the needs for two-person portable power and the lower power end of the vehicle-transportable category, the committee makes the following recommendations:

- The Army should conduct an engineering study of whether a low compression ratio, spark-ignited (or modified combustion chamber) engine (either reciprocating or rotary) is more feasible, considering PMV, cost, and signature, than the diesel engine in the 1.5 to 15 kW range. Commerical components should be used to the maximum extent possible with engine families such as one- two- and four-cylinder engines.

o In view of limited R & D funds, the Army should closely monitor commercial and military developments for rotary and gas turbine engines in the 30 to 50 kW size range and larger. One of the top priorities for R & D funds should be signature suppression for the current prime mover, the diesel engine.

Vehicle Mounted

Viewed from a systems perspective, the diesel engines powering all Army vehicles represent a major and largely untapped source of electrical power in the battlefield. Vehicle-engine-driven (VED) MEP units can be rapidly deployed into new battle zones with the first wave of vehicles until fixed-positioned MEP units arrive, in addition to providing valuable backup power sources to increase power system reliability. Power conditioning makes it possible to deliver regulated output power from such a unit. The committee concluded that onboard power generation using the vehicle engine is relatively inexpensive, practical, and useful, especially if included in the initial design of the vehicle.

Hence, the committee recommends:

o The Army should move as rapidly as possible in the development and use of vehicle-mounted MEP units that provide onboard power generation using the vehicle engine as the power source.

ELECTRICAL TECHNOLOGIES

Commercial developments in electronics are expected that can considerably affect the system power density and mobility of MEP units. As mentioned above, commercial developments in power-conditioning technologies represent a potentially practical and important application to generator sets. Their use can allow alternators to operate at high speeds leading to substantial reductions in generator size and weight. Developments in magnetic materials and low resistivity conductors can also lead to reductions in alternator weight and volume. Advances in superconducting materials may someday lead to substantial reductions in generator set weight and volume and should be closely monitored.

ARMY R & D STRATEGY

In so far as the committee has been able to determine, the Army hasn't yet estimated number, power, and performance (including electrical) requirements for high-performance MEP units (including personal power backpacks as recommended above) suitable for Army 21 use. This estimate is an essential first step for an Army R & D program since high-performance MEP units will not be a non-developmental item (NDI) procurement.

Having established number, power, and performance requirements, two competitive development contracts should be let to design a family, where applicable, of high-performance MEP units that will meet the number, power, and performance requirements. Such items as type of power plant, use of power conditioning, and so forth, should not be specified. At the end of the development contracts, a single design contract should be let to develop the design(s) judged best to meet the Army's needs for the high-performance MEP units.

During this design and development phase for high-performance MEP units, the Army should continue procurement of NDI MEP units, which can use diesel and JP-8 fuels, for use when high-performance MEP units are not required. However, when procuring these NDI MEP units, the Army should recognize that air transportability (and therefore PMV) is, and will continue to be, a significant performance factor for all MEP units and consequently included as a factor in procurement decisions. At the end of the high-performance MEP unit design and development process, the Army should consider performance, cost, parts commonality, and so forth, and decide whether the Army's interests are best served by continuing to have NDI and high-performance MEP units or by gradual conversion to all high-performance MEP units.

TECHNICAL SUMMARY

INTRODUCTION

Mobile electric power (MEP) plants, more commonly called generator sets, is a generic term that includes engine-generator sets, fuel cells, batteries, and thermal-to-electric conversion devices. The MEP engine-generator sets of the U.S. Army range from a fraction of a kilowatt to hundreds of kilowatts and are mobile in that they can be towed behind a vehicle, carried on a vehicle and unloaded, or carried by individual soldiers. The Committee on Mobile Electric Power Plant Technologies had a number of tasks to address (see Appendix A). The committee's main objective was to assess the state of the art of MEP technologies, including technologies likely to become commercial in the next five years and those that may mature by the year 2015. Based on this assessment, the committee recommended research and development strategies for the U.S. Army's Logistics Support Directorate, to ensure the development and fielding of MEP plants that can meet Army requirements for the period from 1990 to 2015. As background, Table 1-1 lists proposed projects of the Directorate and funding for Fiscal Year 1989. Chapter 2 of this report summarizes the role of MEP in the U.S. Army; Chapter 3 addresses desirable requirements for Army MEP systems; Chapter 4 evaluates the component technologies of these systems including engines and power sources and associated electrical subsystems; Chapter 5 develops concepts for MEP units in the Army of future. Appendices B to H present additional technical details regarding component technologies. The following sections relate the principal points of the committee's analysis, including the committee's major conclusions and recommendations.

MOBILE ELECTRIC POWER IN THE ARMY

The Army currently maintains about 133,000 MEP units, ranging from about 1.5 kW to 750 kW and 85 percent of which are less than 10 kW. Most of these MEP units are more than 10 years old and are either gasoline- or diesel-powered. The Army has converted most of its mobile equipment to compression-ignition engines, the main exception being gasoline-powered generator sets of less than 10 kW.

TABLE 1-1 List of Activities that Ft. Belvoir has Planned for 1989 and Beyond. Projected Budget for Fiscal Year 1989 is Indicated.

Project	FY 89 Proposed Budget ($1000s)
Development and Demonstration of Vehicle In-line Generator	450
Demonstrate Technical Feasibility of Personal Power Source (Kerosene Fueled)	200
Pulse Power Technology	350
Materials and Technologies to Reduce Weight and Size of Generator Sets	---
Applications of High-temperature Superconducting Materials	200
Two-man Portable Generator Sets	300
Generator Set Proof of Principle Demonstrations	500
Compact Engine Generator Sets	250
Electric Power Technologies	---
Mobile Hospital Power Plant	200
Power Electronics Technology	150
Advanced Cable Technology	200
Electric Power Distribution System	200
2 kVA Power Conditioner Module	600
Advanced Cabling	200
Integrated Power Systems	400
Enhanced DISE	200
Belt-Driven AC Generator for Vehicle Power	272
TOTAL	4.672

Recently, the policy has been advanced that the Army in the North Atlantic Treaty Organization (NATO), will use a single fuel, the jet fuel JP-8, in the forward battlefield area. For logistic reasons, the Army policy is to procure new combat and tactical vehicles and generator sets only if they operate with diesel or JP-8 fuel. For MEP units, this plan essentially excludes the use of conventional spark-ignition engines and requires more extensive use of diesel-powered generator sets (for example, the Army will procure a fleet of diesel generator sets through the early 1990s to replace the gasoline-powered units). This Army strategy is based on the acquisition of non-developmental items (NDIs), that is, components purchased from the commercial sector, and therefore depends on the worldwide commercial generator manufacturing base.

Another pertinent and major development is the Army's warfare concept for the early twenty-first century, the Army 21 concept. Because of advanced technologies, the battlefield of the next century is envisioned to have combat systems with ranges, lethality, and detection capabilities far surpassing anything known in contemporary warfare. Forces may be exposed to conventional, nuclear, chemical, or biological weapons. Army 21 conflicts will be intense and brief compared to previous wars. In this future battlefield, on which battles are expected to be waged with the integrated systems of all services, mobility will be essential for survival and success. Forces will need to fight in dispersed formations and will depend heavily on battlefield electronics. MEP units of the future Army should therefore have high system power per unit mass and volume (PMV) to minimize weight and space, as well as low noise, infrared, and electromagnetic signatures to minimize detection, acceptable power quality specifications, standardized designs, high reliability, and acceptable costs. Although not investigated by the committee, these attributes would probably be useful in guerilla wars and wars with less technically advanced armies. Current MEP units below 15 kW will not meet the new low-signature requirements. In the committee's judgment, the smaller MEP units, having a probable life of 20 years, will not meet the requirements of the Army 21 scenario.

MOBILE ELECTRIC POWER ATTRIBUTES

The mobility of MEP sets is intimately related to their weight and volume. Achieving higher system PMV will allow greater mobility for generator sets.

The Army 21 premise that detection will increasingly permit rapid destruction implies that signature suppression of both infrared and acoustic energy will take on far greater importance for MEP units. For example, more stringent acoustic signature requirements for new generator sets have been proposed to ensure that noise levels at a specified observer location (300 m has been proposed) are no greater than background sound levels.

Power quality requirements (for example, voltage, frequency) for standard Army MEP sets are generally quite high compared to commercial utility power standards (for example, with regard to voltage regulation). A premium standard for power quality typically results in a decrease in

system PMV. Hence, careful examination of the relationships among power quality, PMV, and mobility may help identify opportunities to enhance mobility.

The ease with which equipment can be supported in the field depends greatly on standardization of design, subsystem modularity, and interchangeable parts. These relationships have been recognized by the Army in MEP procurement practices. Generator sets must also be highly reliable and robust. Furthermore, it is crucial that power be available even in the event of component failure or damage resulting from combat. Last, but not least, MEP plant costs are of extreme importance, especially in light of shrinking defense budgets. The Army has not placed much emphasis on analyzing life-cycle costs (LCC) compared to initial acquisition costs, although the former are more meaningful, incorporating such factors as the cost of fuel over the life of the MEP unit. Both LCC and initial acquisition costs depend on the performance criteria discussed above so that careful design and consideration of trade-offs can help to achieve the proper balance between cost and performance.

CLASSIFICATION OF MOBILE ELECTRIC POWER

To identify Army applications, as well as research and development needs, the committee agreed on a classification scheme for MEP units based on their primary transportation mode. Two major classes of units were defined, namely, man-portable and vehicle-portable. Man-portable units are envisioned to be carried by one person, most likely in a backpack, or carried by two persons. Vehicle-portable units include those that can be towed behind a vehicle, carried on a vehicle and unloaded, or incorporated in a vehicle (for example, an alternator powered by a vehicle engine or an auxiliary power unit). The committee judges that these various classes of MEP plants are required in combat or support duty, with those for the rather wide combat zone envisioned by Army 21 having particularly stringent requirements for high mobility and low signature.

THE SYSTEMS PERSPECTIVE

There may be considerable improvements achieved in PMV by viewing MEP units from the perspective of systems engineering. At the first level, a systems engineering approach to the generator set itself entails the integration of the engine, the generator, and the power-conditioning equipment that produces an acceptable electrical output waveform. Power-conditioning equipment has traditionally been bulky and heavy, playing a limited role in the Army's MEP sets. As a consequence, most standard MEP generator sets rotate at governed speeds no higher than 3,600 rpm to produce the desired 60 Hz output power directly. However, advances in power electronics to reduce their size and weight makes their application to MEP sets more attractive, allowing designs that employ generators operating at higher speeds. Although the committee did not do a detailed design study, it judged that for speeds above approximately 6,000 rpm, significant reductions in generator set size could be achieved. This

achievement is possible because, for a given power rating, alternator weight and volume tend to decrease as the operating speed is increased, which offsets the additional volume required for power conditioning (this additional volume depends heavily on power quality requirements).

Good systems engineering and packaging of the engine, alternator, power electronics, and other mechanical parts may also yield significant increases in system power density. For example, a systems engineering approach to the Advanced Integrated Propulsion System for the Army's next generation of tank power train is projected to increase system power density by about 50 percent over the prior engine design.

The second level of systems integration is that of the engine-generator set and its load. Military standards on power quality for Army MEP sets are quite high compared to commercial utility standards. The military standards typically increase generator set weight significantly. A rethinking of these power quality standards, for example, by shifting the power quality constraint to the load, can increase the PMV and hence the mobility of MEP sets.

The third level of systems engineering is networking (e.g., cable interconnections) among a number of generator sets and loads. Networking techniques may be a way to reduce the overall number of MEP sets and enhance overall power availability and supportability.

Furthermore, the use of onboard vehicle power, that is, the use of an alternator integrated into a vehicle and powered by the vehicle engine, together with stand-alone MEP sets, may prove a workable nonsymmetrical power backup scheme for linking together two different classes of MEP units.

ENGINES AND POWER SOURCES

The committee considered a number of technologies in light of their projected development, for application to MEP sets. These component technologies include different kinds of engines, other power sources, and electrical systems (for more technical details, see Chapter 4). Committee assessments are summarized in this and the next section.

Internal Combustion Engines

Homogeneously Charged Spark-Ignited Engines

Because of the Army policy of using a single fuel (JP-8), the conventional homogeneously charged, spark-ignited (SI) gasoline engine is not suitable for Army MEP applications, in spite of its availability as the power source for many commercial generator sets. However, modification or retrofitting of a homogeneously charged SI engine to yield a low-compression engine that can burn JP-8 fuel may be a practical and worthwhile approach. This modified type of engine would not require a starting motor; run at high speed (6,000 to 8,000 rpm), allowing reduction in alternator size; and have higher fuel consumption, but lower noise levels, weight, and cost than a competing diesel engine. Standard

components and commercial parts could be used. Another approach to using a homogeneously charged SI engine is to modify the combustion chamber, employ charge stratification, and modify the introduction of fuel and air so that JP-8 fuel can be used. Sonex Corporation (Annapolis, Md.) claims to have achieved these modifications (see Chapter 4).

Stratified Charge Engines

Another general category of internal combustion engine is the stratified-charge engine. In a stratified-charge engine the air is unthrottled, the fuel is introduced late in the compression process and, at part load, is initially mixed with only a portion of the air. One approach is to use spark ignition with direct fuel injection. These so-called spark-assisted, direct injection (SADI) engines can be either reciprocating piston or rotary types and are capable of multifuel operation. There has been development of both the piston engine, for example, the Texaco Controlled Combustion System (TCCS), and the rotary engine types. Deere and Company has already advertised a one- and two-rotor military family of generator sets over the power range of 10 to 100 kWe (kilowatts electrical), at speeds of 1,800 and 5,800 rpm, respectively. Not yet in production, their reliability and equipment lifetime are uncertain, but they would achieve major reductions in parts because they are a family of sets.

For power sizes less than 10 kW, development of SADI piston or rotary engines presents a significant challenge in the design of injectors and spark plugs for a small combustion chamber. Inherent thermal efficiency losses, because of the greater surface-to-volume ratio, are also an impediment, and sealing is more of a problem as size decreases. The SADI piston engine would probably have poorer fuel economy and slightly higher power density than a comparable diesel engine. There is development work at Teledyne Continental Motors (Mobile, AL) on small rotary engines (about 2 or 3 kW and larger) without injectors.

Diesel Engines

In the diesel engine, a version of a stratified-charge engine, air inducted into the cylinder is heated during the compression stroke, thus igniting fuel directly sprayed into the combustion chamber. Highly developed, the diesel engine has higher fuel economy than gasoline-powered engines, usually greater initial cost and reliability, and higher noise levels. Diesel engine technology is very mature. Most developments over the next two decades will be aimed at reduced emissions, improved fuel economy, increased system power density and lifetime, and reduced costs and noise levels. Turbocharging is employed in most engines greater than 50 kW, but is not used for smaller engines because of the commercial unavailability and lower efficiency of small turbochargers. There are many commercial diesel-engine-driven generator sets. However, to meet both current and future military standards, they will need major modifications to reduce noise, infrared signature, and weight, and to

improve cold-starting ability. There is no commercial incentive for aggressive development in these areas. Commercial generator sets began at 1 kW and higher.

Stirling Engines

The Stirling engine has been under development for many years for use in generator sets, torpedo propulsion, space power, boat and submarine engines, and bus and automotive engines, but it has not found any significant application except for the reverse Stirling cycle, which is used in cryocoolers. Its potential for relatively quiet operation, multifuel capability, high efficiency, and high power density make it attractive, but it is questionable whether its costs will allow it to be competitive.

Two versions of the Stirling engine have been designed: the kinematic, with a crank and connecting rod mechanism, and the free piston engine (see Chapter 4 and Appendix E). The kinematic engine operating with hydrogen at high pressure is competitive with internal combustion engines in terms of efficiency and power density but problems of cost, complexity of the burner, cooler, and power control systems, and long-term sealing of the hydrogen or helium working fluid are all significant barriers to commercialization. The free piston design is in an earlier stage of development, but has the potential for space power applications, which might lead to a technology suitable for MEP applications. A major Stirling engine development program does not appear to represent a cost-effective investment for the Army's MEP program.

Gas Turbines

Gas turbines are well developed for power levels ranging from hundreds of kilowatts to multimegawatts. They have high power-to-weight ratios compared to reciprocating engines, competitive fuel consumption (for large turbines with regenerators), some multifuel capability, and excellent cold weather starting capabilities. Their high-speed operation makes them attractive for generator sets, because of the reduced size of the alternator that can be achieved at higher speeds. However, there is no large commercial production of turbines in the range of 1 to 300 kW, though the Allison Model 404 regenerative turbine used for the Patriot Missile System generates 150 kW of power. Initial and life-cycle costs are high compared to diesel and those of gasoline engines. There are some gas turbine developments for power plants of about 40 kW, and automotive gas turbine developments are proceeding for values ranging from about 75 to 120 kW. At the present time, low efficiency precludes the use of these engines for MEP sets below 10 kW. The Army does use a 10 kW turbine powered generator set for aircraft starting. Mounted on a cart, the set weighs about 450 kg and costs $25,000. The performance and efficiency of gas turbines would be significantly improved if operating temperatures could be raised from 1100°C (2000°F) to between 1350°C (2462°F) and 1650°C (3002°F). The feasibility of cost-effective, high-

temperature materials, such as ceramics, is being investigated. This technology requires development; the costs and reliability of such ceramics are still uncertain.

Batteries

The Army now uses small primary and secondary batteries for utility purposes (e.g., for flashlights) and small electronic equipment, and larger secondary batteries of the standard lead-acid type for starting internal combustion engines and for vehicle auxiliary power. These batteries include disposable alkaline and lithium cells and rechargeable nickel-cadmium and lead-acid cells, all available commercially. A great variety of battery types are thus already used by the Army. Simplification will be possible if the Army, as it foresees, can standardize around the rechargeable lithium battery in the "universal field battery" proposed for around the year 1995. This battery can be either throwaway or rechargeable. It is projected to have higher energy densities than present cells, can meet other requirements, such as those for electrical current and low-temperature operation, and is expected to be as safe as the lithium cells in the current inventory.

Present lithium (sulfur dioxide [SO_2] and thionyl chloride [$SOCl_2$]) batteries have voltage delays and generate excessive heat. Research and development is directed at solving these problems as well as developing the universal field battery. Development is focusing on materials for the solid cathodes, electrolytes, and solvents. For example, increases in the conductivities of dissolved salts as electrolytes can enhance current densities. The aim is to develop and field a universal field battery within 10 years. These batteries could be used for man-portable, personal power packs (see Chapters 4 and 5), providing enough energy for a typical 12-hour mission.

Fuel Cells

A fuel cell is an electrochemical converter akin to a battery, but unlike the latter, its two electrodes consume an externally supplied fuel and oxidant, whereas in a battery the electrodes are consumed. Fuel cells, which can be arranged in stacks, each consist of two electrodes with an immobilized electrolyte layer between them. The electrolyte can be acid or alkaline, molten carbonate, or solid oxide. Noise and infrared signatures of fuel cells are low, but their requirement to use hydrogen, methanol, or ammonia necessitates the use of a heavy, complex fuel processor if JP-8 fuel is used. A breakthrough by 2015 that would allow direct use of conventional fu [illegible] is probably unlikely. In the commercial sector, fuel cell development is expected to continue.

It is the judgment of the committee that the general use of fuel cells for MEP is impractical. However, fuel cells may have a limited role for man-portable, personal power for those applications where batteries have insufficient energy storage. The fuel, hydrogen, could be supplied as in batteries, that is, in a light-weight cylinder, using advanced reversible

hydrides, or lithium hydride-water generators. Small units like these are being developed by the National Aeronautics and Space Administration for extravehicluar activity in space. They are being developed at present, and being sold commercially, by Ergenics, Inc. (Wyckoff, N.J.). Unit cost would undoubtedly be high, but the alternatives have significant drawbacks. The ultimate practicality of this approach will be determined by battery developments sponsored by the Army and others and by fuel cell developments, whose costs exceed current Army MEP research funds.

Nuclear Power and Thermal-to-Electric Devices

Nuclear power was considered as a possible approach to MEP, ir the form of converting nuclear energy to electricity using thermoelectric devices, solid-electrolyte cells, or heat engines operating on a Brayton, Rankine, or Stirling cycle. Based on considerations of cost, safety, and weight, the committee concluded that, below 1 MW, there is little chance for nuclear MEP systems to be developed for Army use by the year 2015.

The conversion of heat to electricity, by burning JP-8 fuel and using thermocouples, is one possible approach to MEP sets. Such devices would be quiet and require no moving parts, but their low efficiency would result in low PMV. One company has developed a prototype 100 W unit that weighs 21 kg with fuel for a 12-hour mission. These devices are not commercially available and their cost is high.

Conversion of heat to electricity using thermionic diodes has many of the desirable attributes of using thermoelectric devices, but requires a high-temperature source of heat; hence, this approach is considered impractical for MEP.

Nernst devices use a high-temperature source of heat to develop a separation of ions and a resultant electric potential gradient. As discussed in Chapter 4, an alkali metal thermoelectric converter (AMTEC) of mature design should have an efficiency of 20 to 40 percent, a power density of 0.5 kW/kg, no moving parts, and high durability. Until a long lived, high-power porous electrode is developed and demonstrated, AMTEC cannot be considered a practical candidate for MEP.

Conclusions

No single power source meets all the mobile electric power plant requirements of high power density, good fuel economy, a reasonable commercial production base, the ability to use JP-8 as a fuel, acceptable acoustic and thermal signatures, and reasonable initial and life-cycle costs. Furthermore, no single prime mover offers a clear advantage for all MEP sets. The optimal prime mover will differ, depending on the required power output, specific application, and importance of signature, power density, and power conditioning.

With regard to engines and direct energy conversion devices, the committee reached the following main conclusions:

o Active noise attenuation will be required for MEP engines if they are to meet Army 21 combat zone requirements for signature detectability.

o Additionally, the high PMV required for the lower power MEP units cannot be met using nondevelopmental item engine-generator sets. NDI engine-generator sets without enclosures can be used for support zones.

o No gain in PMV of alternating current systems results from operating engine-generator sets between 3,600 rpm and approximately 6,000 rpm. In this speed range and above, power conditioning is required, and within this range the decrease in alternator size is insufficient to offset the volume and, to a lesser extent, weight requirement of the power conditioner.

o Between approximately 10 and 300 kW, commercial diesel engines seem adequate to meet the Army's needs for low-cost, high power density engines, using enclosures for combat zones. In the range of 1.5 to 40 kW, families of diesel engines (a 1.5, 3, and 6 family and 10, 20, and 40 kW family) appear to be feasible. The family concept should have increments based on commercial engines and generator units. The lower range family must meet all combat zone requirements, is not commercially available, and will require development. For transport reasons, gas turbines would be the most likely engines for MEP units larger than 300 kW.

o Diesel engines have the best fuel economy, moderate to low power density, ability to use JP-8 fuel, and are available commercially. They also have low initial and life-cycle costs.

o With the exception of the rotary engine, stratified-charge engines other than the diesel, are not sufficiently developed for production. For the lower power range (less than 10 kW), it is not clear that the required injection and ignition components can be designed for the smaller combustion space of any spark-ignited, stratified-charge engine. The rotary engine can burn JP-8 fuel and would have reasonable fuel economy and acceptable initial (but unknown life-cycle) costs.

o The development of a homogeneously charged, spark-ignition engine that burns JP-8 fuel in the 1.5-to-10 kW range appears to be one approach for achieving low-signature, high-PMV engines at reasonable cost. This engine could use a low compression ratio (around 5: 1) or new technology along with some charge stratification, such as the Sonex system. The low-compression-ratio engine would have poorer fuel economy than a diesel, but should have lower initial costs and less weight.

o A nonregenerative gas turbine, when combined with high-speed electrical equipment and power conditioning, would have the highest power density of all of the systems and could burn JP-8 fuel, but is not commercially available at the low power levels needed for MEP sets. Even if these sets were available commercially, they would have high initial and life-cycle costs and, especially in the low-power range (of about 1 to 20 kW), poor fuel economy. Efficiency gains would be achieved with higher pressure ratios and higher inlet temperatures. Regeneration would markedly increase thermal efficiency, but also bulk and, to some degree, weight.

o Stirling engines have minimal acoustic and thermal signature problems, and can burn JP-8 fuel. They achieved low fuel consumption in laboratory demonstrations for kinematic Stirling engines but they are not available commercially or ready for production. They will probably have

power densities comparable to that of the diesel, with equal or higher first costs and unknown life-cycle costs.

o Batteries or fuel cells using a disposable hydrogen fuel container are the preferred candidates for personal backpacks (in the range of hundreds of watts), with fuel cells suitable only when battery energy storage capacity is inadequate. Fuel cells are not suitable for larger sizes because, among other problems, they cannot effectively use JP-8 as a fuel.

o Nuclear energy, thermionic, and Nernst devices are not considered practical for MEP applications based on their power density, weight, cost, and safety.

ELECTRICAL SYSTEM TECHNOLOGIES

A prime mover such as an engine needs a generator to convert the mechanical motion of the engine into electrical energy. Alternators can be made smaller and lighter by running them at higher speeds, but are limited to 3,600 rpm if 60-Hz alternating current is required. Electronic power conditioning will be necessary if rotational speeds higher than 3,600 rpm are required. However, reductions in generator size will not compensate for the added power-conditioning volume until approximately 6,000 rpm.

Reductions in alternator weight and volume could also be achieved by using permanent magnets to create the magnetic field on the alternator's rotor; rare-earth permanent magnetic materials can aid in this development. The development of materials with much lower electrical resistance than those now available, coupled with new materials other than iron to shape the magnetic field, may also yield substantial savings in weight. Superconductors may contribute to this development; progress in high-temperature superconductors should be monitored for alternator application. Active cooling technologies, such as those used in the generating systems of aircraft, could also significantly reduce weight and volume.

As a result of improving technologies, it is increasingly practical to combine a high-speed generator with output power conditioning. Accelerated developments are taking place in new classes of power semiconductors (power switches), in "smart power" integrated circuits, and in high-frequency converter circuits. Applying these advances to power conditioning can substantially reduce the bulk, weight, and number of parts of the power-conditioning system required to produce acceptable output waveforms. For example, the U.S. Air Force is sponsoring a multiyear development project to apply advanced power electronics technology, which is expected to double the power density of the 400-Hz variable-speed, constant-frequency generating equipment used in the F-18 fighter plane. The costs of these new technologies are high, but are expected to decline as development occurs.

The type of load and required power quality significantly affect alternator size and weight. For example, to start a 5-kW motor while retaining reasonable power quality, alternator power must approach 10 kW. Unnecessarily high power quality standards and lack of load control can markedly affect PMV.

Conclusions

o Alternator size can be reduced significantly by operating at speeds above about 6,000 rpm, but power conditioning is then required. At these higher speeds, new electrical power-conditioning technologies can substantially reduce generator size and weight. New magnetic materials, low-resistivity conductors, and active cooling could all lead to substantially decreased alternator weight and volume.

o Reducing power quality requirements when possible, and using load control, can also significantly reduce alternator system size and weight.

FUTURE MOBILE ELECTRIC POWER SYSTEMS

The Army 21 concept may generate the need for individual soldier backpacks, probably in the range of several hundred watts, but there is now no satisfactory source of personal power of less than one kilowatt. Batteries can supply limited energy and power. They might be used for a typical 12-hour mission with advanced lithium batteries projected to weigh about 4.5 kg. Small internal combustion engines are noisy and use gasoline rather than JP-8 fuel. Also, reducing their signatures to acceptably low levels would markedly increase their costs, mass and volume. Use of Stirling engines, sodium heat engines, and nuclear devices are possible approaches, but the committee judged them to be, for the most part, too impractical. Fuel cells are another possibility, although they require scarce materials and exotic fuels, and are not in quantity production.

Committee judgments differed on the relative practicality of small engine-generator sets for man-portable backpacks. The majority, but not all, of the committee concluded that small engine-generator sets were impractical and that batteries and fuel cells were potential candidates.

In view of the above observations, the Army should carefully review the requirements for personal power for individual soldiers, specify needs such as power and signature, and weigh the advantages of personal power with its development costs. This review should recognize that small power requirements (tens of watts) could be met by available and future batteries but also that higher power requirements would require a replaceable fuel source.

If this review shows that personal power is cost-effective, and if the power required is more than can be supplied by batteries, development funds will be required. For this situation, committee opinions differed. A minority judged that less development would be required to modify small internal combustion engines, to reduce noise and allow use of JP-8 fuel, than to develop a personal-power, hydrogen fuel cell. The majority judged the reverse. There was complete agreement that completion of the recommended review would clarify the optimal solution for man-portable power.

Larger man-portable MEP sets, in the range of about 1 to 7 kW for use near the battle front, will require maximum system performance in signature, weight, and volume, because of their mission and location. The committee judged that diesel and low-compression spark-ignited engines are

the primary prime-mover candidates for these MEP units. The diesel engine is probably heavier and more expensive than the spark-ignited engine but would have better fuel economy. For larger engines (for towed MEP units), the best current prime mover is the diesel engine, but developments in rotary and gas turbine engine technologies may change this situation.

The committee judged it important to consider taking advantage of the engine horsepower already present in vehicles. Vehicle-mounted units, that is, generators built into and powered by truck engines, could take advantage of the large amount of available onboard vehicle power in the Army fleet. This approach provides additional power and is relatively inexpensive, and practical, especially if considered in the initial vehicle design.

MAJOR CONCLUSIONS AND RECOMMENDATIONS

Conclusions

o The supply of electric power for the needs of Army 21 is of critical importance to the Army's mission.

o It appears that high-performance mobile electric power is not considered essential to the Army's strategic thinking regarding Army 21. The continuation of current procurement practices and development policy will not result in a fleet of high-performance MEP units that meets the needs of Army 21. Special purpose MEP units will require military research and development.

o To meet future battlefield requirements, the Army will need a family of MEP sets not now commercially available, having high system performance characteristics, that is, having low signature, high power density, and easy transportability, in addition to MEP sets having less stringent performance characteristics.

o To date, the Army has not addressed and quantified the type, quality, and magnitude of MEP power requirements needed under the Army 21 scenario. This information would have helped the committee to make more specific recommendations.

o Currently, there is no satisfactory source of personal power of less than one kilowatt, except for batteries at small power levels. All sizes of MEP sets, except possibly man-portable backpacks, will have to meet the JP-8 fuel requirement. Backpacks will probably use direct energy conversion devices. Batteries are preferred although fuel cells using disposable hydrogen containers should be considered if power levels are required for which battery energy storage capabilities are insufficient.

o To achieve high-performance systems, integration of prime mover and electrical generator, modified power quality requirements, involving load integrated power conditioning as well as special signature reduction treatment not commercially available, will be needed.

o Nuclear power, thermionic, and Nernst device technologies are not considered practical for the mobile power needs of the Army.

o The most attractive prime movers for MEP units are the diesel, rotary, gas turbine, and low-compression spark-ignition engines. In the range of 1 to about 15 kW, rotary and gas turbine engines are not

attractive, while the low-compression, spark-ignition engine is not attractive above about 10 to 20 kW.

o In the range of 1 to between 10 and 15 kW, Army 21 power needs are ill-defined, and technology does not provide a clear choice between the diesel and low-compression, spark-ignited engine.

o Because of restricted funding, the wide range of MEP sets needed, the need for high-performance systems, and the relatively small number of units over which these costs can be spread, the Army will have to be extremely selective in using its development funds.

o For greater power (of 15 to 300 kW), the best current prime mover is the diesel engine. Both military and commercial developments are underway in rotary and gas turbine prime mover technologies, which could change this situation. Gas turbines are the most likely candidate for MEP units larger than 300 kW.

o Vehicle-mounted onboard power generation using the vehicle engine is relatively inexpensive, practical, and useful, especially if considered in the initial design of vehicles.

Recommendations

o The Army should integrate the needs for mobile electric power supply, as dictated by the Army 21 scenario, into its overall strategic planning. This requires that a central authority be established having responsibility for an overall development plan for how MEP technologies should be integrated into Army 21.

o As long as there are only limited R & D funds, the Army should closely monitor commercial and military developments in rotary and gas turbine engines in the range of 30 to 50 kW and greater. Top priority for R & D funds should be signature suppression for the current prime mover, the diesel engine.

o The Army should carefully study its present power quality requirements, keeping in mind power-conditioning possibilities in both production and use of electricity, and, recognizing the system performance implications, should establish new power quality requirements for high-performance systems.

o For all power sizes, the Army should evaluate the costs and benefits of integrating the prime mover and alternator in view of the need for high-performance systems.

o The Army should conduct an engineering study of the relative feasibility of a low-compression-ratio, spark-ignited (or modified combustion chamber) engine (either reciprocating or rotary) and the diesel engine in the range of 1.5 to 15 kW. Commercial engines should be used in this po\ -- range to the extent possible, notably engine families such as one-, two-, and four-cylinder engines.

o The Army should study its need for personal man-portable MEP units. If their power requirements exceed battery capability, the use of fuel cells with disposable hydrogen cartridges are judged by the committee to be the most viable potential candidate, although high-speed engines and other conversion devices might be possible. Army battery development for

personal power should continue at the current level, since the technology is promising for low power needs (of approximately less than 150 W).

o The Army should move as rapidly as possible in the development and use of onboard power generation, using the vehicle engine as the power source.

2

INTRODUCTION TO MOBILE ELECTRIC POWER IN THE ARMY

Like society at large, modern armies have become increasingly dependent on electrical energy. Nearly all weapons, communications, and support systems are dependent on a source of electric power.

The Army currently maintains approximately 133,000 mobile electric power (MEP) units, ranging from 1.5 kW to 750 kW. About 85 percent of these are less than or equal to 10 kW, have standard components and parts, and operate on standard issue diesel or gasoline fuel. In the near future, for logistic reasons, all engine generator sets must use diesel fuel. Because they employ technologies more than 20 years old, they are not well matched to current Army operational realities--a mismatch that can be expected to become more severe in the future.

This study involves an assessment of the potential impact of the developments in energy conversion technologies on the nature of mobile electric generating plants that the Army will purchase in the 1990 to 2015 time period. Developments in conventional systems as well as emerging energy conversion technologies will provide key performance improvements. The committee considered two main classes of systems needed to meet the long-term needs outlined by Army 21 Doctrine: man-portable and vehicle-portable units.

ARMY LONG-TERM NEEDS AND DOCTRINE

Army 21

Army 21 is the U.S. Army's warfare concept for the early twenty-first century. Quoting from the Army 21 concept draft provides some indication of the conflict envisioned (Higgins et al., 1987):

"The battlefield of the 21st Century will be dense with sophisticated combat systems possessing ranges, lethality, and employment capabilities that surpass everything known in contemporary warfare, the airspace over the battlefield will be saturated with aerial and space weapons, surveillance, reconnaissance, and target acquisition systems. Conflicts will be intense and devastating particularly at the point of decisive battle."

Army 21 characterizes the forces as being fully integrated and fully dispersed (Higgins et al., 1987):

"No single weapon will be fielded to dominate the total battle. The battle will be waged with integrated systems from all services. Rapid battlefield mobility will be absolutely essential for success. The future battle will reflect the growing proliferation of nuclear, chemical, and biological weapons, coupled with the enemy's apparent permissive attitude regarding employment of these weapons such as those involving directed energy. Therefore, it is imperative that forces plan from the start to fight dispersed on this "conventional-nuclear-chemical-biological-electronic battlefield" and concentrate only when necessary for decisive action."

The Army 21 commander, to be successful, must use: "... agility, deception, maneuver, firepower and all the other tools of combat ... to present the enemy with a succession of dangerous and unexpected situations faster than he can react to them." This Army 21 conflict in the twenty-first century will be intense and short in duration in comparison to previous wars and will clearly require electric power generation capability that is mobile. Such MEP units will also be useful for guerilla war and wars with less developed armies.

The present report outlines a strategy for the Army to develop man-portable and vehicle-portable MEP units to provide electric power that is equal in mobility to vehicles in the Army combat and tactical forces.

Fuels Policy

The Army fuels policy is important to this study since it defines and limits the types of feasible energy conversion devices in the time frame 1990 to 2015. Diesel fuel for U.S. Army and other Department of Defense ground equipment is procured under Federal Specification VV-F-800 C (covering fuel oil and diesel), which specifies four grades: DF-A, DF-1, DF-2 (CONUS), and DF-2 (OCONUS). Grades DF-A and DF-2 (OCONUS) are intended for use in the Arctic and Europe, respectively. Grades DF-1 and DF-2 (CONUS) are intended for use within the 50 states and are essentially the same grades that industry provides for civilian users under ASTM D975 standard for diesel fuel (LePera, 1985).

For logistic reasons, the Army policy is to procure all new combat and tactical vehicles and generator sets only if they operate with diesel fuel. Recently, the policy has been advanced that, the Army in concert with the North Atlantic Treaty Organization (NATO), will use a single fuel, the jet fuel JP-8, in the forward battlefield area. This military fuel policy has a major impact on the future research and development (R & D) and procurement policies for MEP units.

Output Power Frequency Standardization

The Army has announced its plans to adopt 60 Hz as the standard output frequency for all future MEP generating equipment. Logistical advantages are expected to result from this policy by eliminating problems associated with supplying power to combinations of 50 Hz, 60 Hz, and 400 Hz equipment in the field. Elimination of 50 Hz would cause some problems with NATO interoperability or require power conditioning. Sixty Hz is attractive as the standardized frequency since standard domestic utility power can be used to supply Army loads whenever necessary or convenient. There are also cost advantages in 60 Hz standardization.

Although the committee accepted the 60 Hz standardization as a basic assumption in conducting this study, there are weight and volume penalties associated with the choice of 60 Hz that deserve noting. In particular, basic 60 Hz electrical equipment including transformers and filter reactors are much larger and heavier than equivalently-rated 400 Hz components as a result of the frequency difference. It is this weight to volume advantage of 400 Hz equipment that accounts for its widespread application in airborne electrical systems. The cost premium associated with land-based 400 Hz equipment might be justifiable to the extent that Army 21 policies demand the lowest possible weight and volume for maximum battlefield mobility.

The 60 Hz standardization policy is not intended to prevent the development of Army MEP equipment that fundamentally requires specialized power sources. For example, man-portable personal power units are likely to use some type of direct electrochemical converter delivering DC power, as described later in this report. Despite such exceptions, the 60 Hz standard can be expected to gradually improve battlefield electrical compatibility logistics by curtailing the introduction of new loads requiring 50 or 400 Hz power.

INTRODUCTION TO CURRENT INVENTORY

Eighty percent of the present Army generator sets use gasoline as a fuel, seventy percent is over 10 years old, and all do not meet the latest user requirements. There has been no Military Standard (MIL-STD) procurement since fiscal year 1984 (FY84) and it appears that budget cuts in FY88 and FY89 will further delay the modernization of the electric power generator fleet. Figure 2-1 shows the density and age distribution of existing generator sets. The data show that the gasoline-fueled sets are older than the diesel-fueled sets and much larger in number.

CLASSIFICATION OF ARMY MOBILE ELECTRIC POWER

Army MEP plants come in a wide variety of ratings and sizes, designed for a variety of transportation modes and mission purposes. In preparation for carrying out the planned MEP study, it was first necessary for the committee to define a consistent set of classes to encompass the complete range of Army MEP plants. Care was taken to provide sufficient breadth in

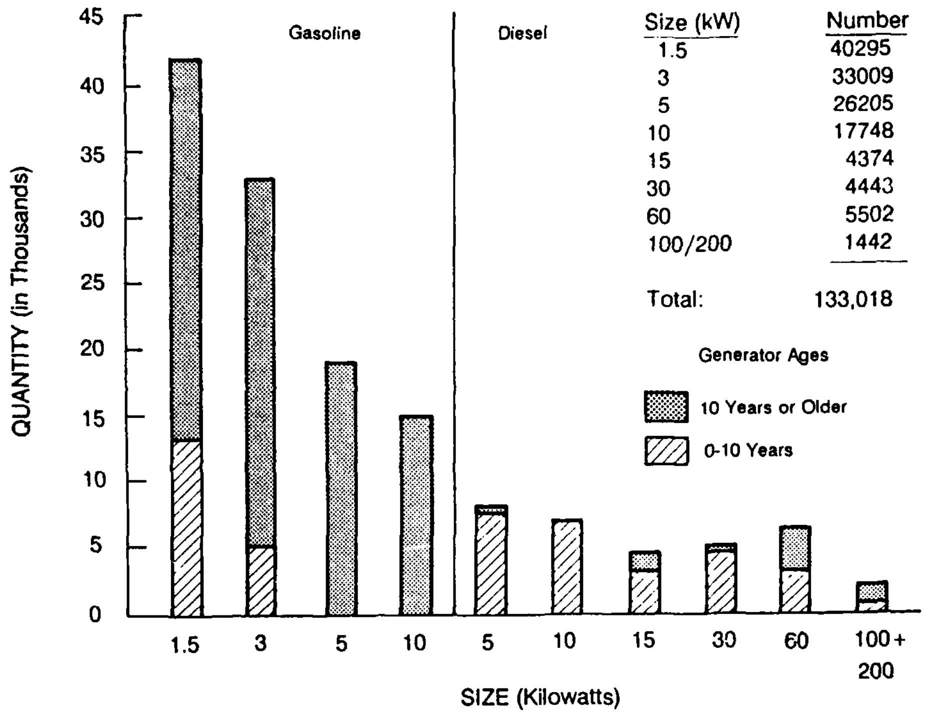


FIGURE 2-1 Density and age of Army generator sets.

this classification to include both currently fielded units and likely future needs.

The resulting set of MEP plant classes adopted for this study is shown in Figure 2-2, illustrating both the hierarchy and the approximate power ranges for each of the classes and subclasses. Although this classification structure is similar to the power source classes defined by the Army Logistics Support Directorate at Ft. Belvoir, the differences reflected in Figure 2-2 are associated with the specific needs of this study. The horizontal axis of this figure is scaled to indicate the approximate ranges of rated power levels for each class and subclass of MEP units, based on projections for the 1990 to 1995 period. The relative positions of these power ranges probably carries more significance than the specific values of the endpoints since changing Army requirements and new technology capabilities are certain to shift these boundaries during coming years.

Figure 2-2 shows that, at the top of the hierarchy, all MEP plants fall into one of two major classes: man-portable or vehicle-portable. As the names imply, these two classes are distinguished by the transportation means employed to deliver the power plant to its site of use. It should be no surprise that the power range for the man-portable power plants are limited to very modest power levels compared to the vehicle-portable units.

Figure 2-2 also indicates that the man-portable power plants are broken down into subclasses of personal and two-person units. These subclasses are meant to distinguish not only the number of soldiers necessary to transport the power plant, but also the level of integration into the soldier's combat equipment. Whereas the two-person power plants are hand- or shoulder-carried to the use site where they are energized, the personal power units are most likely designed into a backpack where they can deliver power while a soldier is moving as part of a combat mission.

The vehicle-portable units are broken into two major subclasses: vehicle-mounted and vehicle-transportable (Figure 2-2). The vehicle-mounted power plants are permanently attached to the vehicle so that the unit necessarily goes wherever the vehicle goes. In contrast, the vehicle-transportable subclass identifies all the power plants that are designed to be delivered as independent units to their use site by an Army vehicle, which can then depart.

The vehicle-mounted subclass can be further distinguished as vehicle-engine-driven (VED) or auxiliary power units (APU). Drawing on the Army definitions, the VED electric power sources use the vehicle's propulsion engine as its prime mover, either directly (e.g., in-line drive) or indirectly (e.g., belt-driven). The APU is also permanently mounted in the vehicle, but uses a dedicated engine rather than the vehicle propulsion engine.

In a similar fashion, the vehicle-transportable subclass can be further subdivided into towed and carried units. The towed power plants are typically mounted permanently on a trailor that can be conveniently disconnected from the vehicle at the use site. These towed units include the largest power plants in the Army inventory. The smaller carried power plants are transported in the vehicle's cargo compartment and then removed at the installation site. While the MEP units at the lower end of this

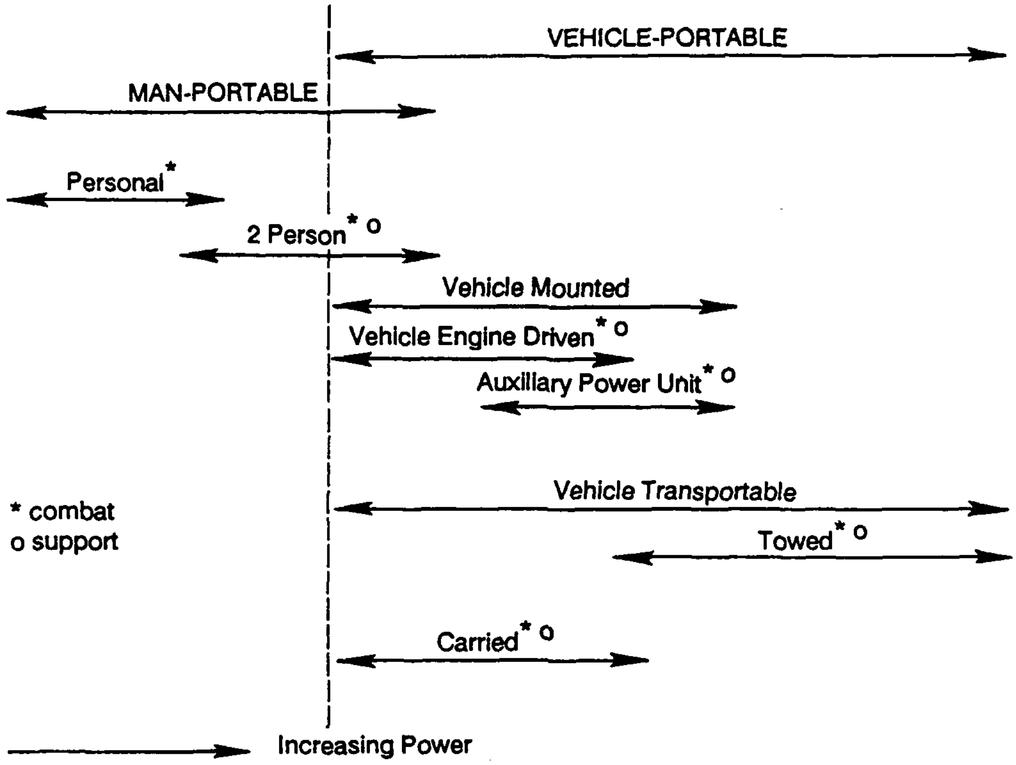


FIGURE 2-2 Classification of Army mobile electric power sources.

carried range can be unloaded by one or two soldiers, the larger carried units must be unloaded using a winch or alternative mechanical aid.

Each of the MEP plant subclasses has been designated as required for service in combat or support duty, or both. Since combat duty entails operation on the frontlines of the battlefield, MEP units designed for such use have particularly stringent demands for high mobility and low signature. As Army 21 detectability predictions become realities, these requirements will gradually be extended by necessity to the support units operating some distance away from the frontlines as well.

Although weight is not explicitly plotted on Figure 2-2, it should be pointed out that weight as well as power increases from left to right in this figure. In fact, the specific maximum rated power endpoints of the man-portable subclasses as well as the one- or two-man-unloadable units are directly determined by the maximum weights that the soldiers can carry or unload. As technology improves the achievable mass power density of these MEP power units, the maximum rated power endpoints for these classes will increase proportionately. In a similar manner, volumetric power density characteristics will play a dominant role in determining the maximum rated power endpoints for the VED MEP units because of space limitations in the engine compartments of standard Army vehicles.

The MEP plant classes designated in Figure 2-2 will be used throughout the remainder of this report to identify specific categories of Army MEP uses and needs.

KEY SYSTEM CHARACTERISTICS AND PERFORMANCE CRITERIA

The purpose of this section is to highlight key MEP system characteristics and performance criteria that broadly apply to current and future MEP equipment inventories. Despite exceptions and additions for special units, the following characteristics summarize key criteria for evaluating current and future generations of MEP systems. The order of description does not necessarily imply priority, which varies depending on the final application.

System Power Density

Generator set power density, evaluated in terms of power per unit mass and volume (PMV), is tightly coupled to the equipment mobility characteristics. Hence, MEP equipment requiring superior mobility characteristics demands high equipment PMV as a key prerequisite condition. For example, a man-portable power pack carried on a battlefield by a single foot soldier must weigh as little as possible. However, high mass power density alone does not guarantee favorable mobility; an MEP unit must be designed to achieve high mobility, using high PMV as an important means for achieving this end. High system PMV must be carefully balanced against other important objectives such as high reliability and low manufacturing cost, which are tightly interrelated in the equipment design.

MIL-STD-1332B (March, 1973) includes information on maximum dry weights for tactical generator sets in the Department of Defense (DoD) MEP Engine Generator Set Family (Table 2-1). Mass power density values range from 11 W/kg (5 W/lb) for 0.5 kW units to 51.7 W/kg (23 W/lb) for 750 kW units. Future improvements in these mass power density characteristics are expected to be particularly crucial for units at the lower end of this power range where mobility requirements become extremely challenging for man-portable applications. In addition, the concept of mass energy density is very important for evaluating future developments of man-portable power units since such units must be capable of delivering a specified power level for a required mission duration without overburdening the soldier.

Signature

Sensor technology breakthroughs anticipated according to the Army 21 doctrine greatly increase the relative importance of acoustic noise and infrared (IR) radiation suppression characteristics in future generations of Army MEP equipment. If one accepts the Army 21 premise that detection will increasingly dictate rapid destruction, then signature suppression (both acoustic and IR) takes on very high significance for all combat-zone equipment. Although signature standardization might be another option, the best strategy is to try to reduce signature. If the detectors are better than the signature suppressors, the target is vulnerable.

Standard DoD MEP generator sets currently in the field tend to be noisy (85 dB[A] at 7 m) with little or no IR shielding. Since such shielding adds weight, signature suppression has clearly been of secondary importance in the design of past generations of Army MEPs. However, tightened community noise standards in Europe are making it necessary to specify quieter MEP units for upcoming procurements (70 dB[A] at 7 m). It should be noted that the acoustic signature requirements for these units are specified in terms of "A-weighted" decibel (dB[A]) units, which represent a weighted summation of the acoustic spectral content. These are the same units typically used to rate noise generation in commercial equipment.

Growing concern about the signature detection capabilities of future battlefield weapons has led to development of improved means for specifying equipment signature characteristics in terms of acoustic non-detectability limits (Garinther et al., 1987). The purpose of such non-detectability limits is to ensure that generator set noise is no greater than the background sound level at a specified observer location. Under such conditions, the listener cannot distinguish the generator set noise from background sound.

These acoustic non-detectability limits are designed to be more meaningful than typical commercial noise limits by placing specific requirements on the acoustic spectral content. For example, non-detectability limits developed by the Army Human Engineering Laboratory (Garinther et al., 1987) are expressed as maximum linear sound pressure levels allowed at one-third-octave center frequencies from 50 Hz

TABLE 2-1 Maximum Dry Weights for Tactical Generator Sets

kw Rating	Maximum Dry Weight[a] (kg)	Power/Weight (W/kg)
.5	45	11
1.5	68	22
3.0	136	22
5.0	499	10
10	635	15.7
15	1,360	11
30	1,587	18.9
60	2,268	26.5
100	3,175	31.5
150	4,082	36.7
200	4,762	42
500/750	14,512	34.5/51.7

[a] Maximum dry weight is the weight of the generator set less fuel, coolant, lubricant, electrolyte, and optional equipment. Optional equipment weights are shown in MIL-STD-633 (1974).

to 10,000 Hz. More details about the nature of these specifications are provided in Chapter 3.

The committee has received no evidence indicating that the more specific acoustic non-detectability limits will be applied to new MEP unit purchases in place of the more conventional and broader dB[A] limits. In addition, plans call for suppression of IR signatures of these new MEP units my means of auxiliary nets placed over the equipment instead of integral IR shielding measures.

Power Quality

Power quality requirements for standard Army MEP units as set by MIL-STD-1332B generally match or exceed commercial utility power quality standards. For example, voltage regulation requirements specified by MIL-STD-1332B for the four classes ac power range from 1 to 4 percent, whereas commercial utilities are typically required to achieve no better than 3 percent regulation. A summary of the principal power quality requirements contained in MIL-STD-1332B is provided in Table 2-2.

These requirements provide electrical load designers the luxury to assume that high power quality will always be available placing the burden for ensuring adequate power quality on the generator capabilities rather than on the load requirements (Higgins et al., 1987). Thus, each standard MEP unit is designed to supply power, typically with a conservative margin in power quality, to a wide variety of loads without further modifications of either the load or generator set. Maintaining adequate power quality while starting load motors places particularly demanding requirements on generator design because of large transient currents drawn during such startups.

Since any premium in power quality typically adds to the power plant weight, the close coupling between power quality, power density, and mobility calls for reexamination in light of current requirements. A fresh look at the interrelationships between these system design factors is presented in Chapter 3 (see System Perspectives section), including opportunities for enhanced power plant mobility through modification of the existing power quality systems philosophy.

Supportability

Supportability in this context refers to the ability of the Army during wartime conditions to efficiently field and maintain (i.e., support) the required inventories of MEP equipment. As such, the supportability of Army MEP equipment is strongly dependent on such factors as standardization of design, subsystem modularity, and parts interchangeability. For example, a proliferation of generator set models creates the need for large inventories of spare parts that must be supported in the field under combat conditions.

TABLE 2-2 Principal Military Standard (MIL-STD-1332B) Power Quality Requirments

CHARACTERISTIC PARAMETER	PRECISE CLASS 1	UTILITY CLASS 2A	CLASS 2B	CLASS 2C	DC
A. VOLTAGE CHARACTERISTICS					
1. REGULATION (%)	1	2	3	4	4
2. STEADY-STATE-STABILITY (VARIATION) (BANDWIDTH %)					
(A) SHORT TERM (30 SECONDS)	1	1	2	2	2
(B) LONG TERM (4 HOURS)	2	2	4	4	NA
3. TRANSIENT PERFORMANCE					
(A) APPLICATION OF RATED LOAD					
(1) DIP (%)	15	20	20	30	30
(2) RECOVERY (SECONDS)	0.5	3	3	3	2
(B) REJECTION OF RATED LOAD					
(1) RISE (%)	15	30	30	30	40
(2) RECOVERY (SECONDS)	0.5	3	3	3	2
(C) APPLICATION OF SIMULATED MOTOR LOAD (TWICE RATED CURRENT)					
(1) DIP (%)	30	NA	40	NA	NA
(2) RECOVERY TO 95% OF RATED VOLTAGE (SECONDS)	0.7	NA	5	NA	NA
NOTE: THE VOLTAGE SHALL STABILIZE AT OR ABOVE THIS VOLTAGE (NOT APPLICABLE TO ALL SETS RATED 5 kW OR SMALLER, OR 500 kW AND LARGER).					
4. WAVEFORM					
NOTE: SPECIFIED VALUES ARE FOR THREE PHASE OUTPUT; FOR SINGLE PHASE, ADD ADDITIONAL 1%.					
(A) MAXIMUM DEVIATION FACTOR (%)	5	5	5	6	NA
(B) MAXIMUM INDIVIDUAL HARMONIC (%)	2	2	2	3	NA
(C) RIPPLE VOLTAGE (%)	5.5				5.5
5. VOLTAGE UNBALANCE WITH UNBALANCED LOAD (%)	5	5	5	5	NA
NOTE: WITH GENERATOR SET CONNECTED FOR THREE PHASE OUTPUT AND SUPPLYING A SINGLE LINE-TO-LINE, UNITY POWER FACTOR, LOAD OF 25% OF RATED CURRENT AND WITH NO OTHER LOAD ON THE SET. (NOT APPLICABLE FOR SINGLE PHASE CONNECTIONS OF SETS.)					
6. PHASE BALANCE VOLTAGE (%)	1	1	1	1	NA
7. VOLTAGE ADJUSTMENT RANGE (%) (MIN)	-5 +17	+/-10	-5 +17	-5 +5	
NOTES: FOR 400 HZ SETS, UPPER VOLTAGE ADJUSTMENT IS +10% OF RATED VOLTAGE. FOR 50/60 HZ SETS OPERATING AT 50 HZ, UPPER VOLTAGE ADJUSTMENT MAY BE LIMITED TO 220/380 VOLTS (≤ 200 KW) AND 2200/3800 (> 200 KW).					
VALUES SHOWN IN CLASS 2B ARE FOR SETS RATED AT 15 KW AND ABOVE.					
THE VOLTAGE ADJUSTMENT RANGE FOR DC IS 23 TO 35 VOLTS AT NORMAL AMBIENT TEMPERATURES AND +5 PERCENT OF NOMINAL (28 VOLTS) AT EXTREME TEMPERATURES.					
B. FREQUENCY CHARACTERISTICS					
1. REGULATION (%)	0-3 ADJ'ABLE	0-5 ADJ'ABLE	3	3	NA
2. STEADY-STATE-STABILITY (VARIATION) BANDWIDTH %)					
(A) SHORT TERM (30 SECONDS)	0.5	0.5	2	4	NA
(B) LONG TERM (4 HOURS)	1	1	3	4	NA
3. TRANSIENT PERFORMANCE					
(A) APPLICATION OF RATED LOAD					
(1) UNDERSHOOT (%)	4	4	4	4	NA
(2 RECOVERY (SECONDS)	2	4	4	4	NA
(B) REJECTION OF RATED LOAD					
(1) OVERSHOOT (%)	4	4	4	5	NA
(2) RECOVERY (SECONDS)	2	4	4	6	NA
4. FREQUENCY ADJUSTMENT RANGE (%) (MIN) (WHERE REQUIRED)	+/-3	+/-4	+/-3	+/-3	NA

SOURCE: SAIC (1988)

The importance of supportability was recognized by the Army following the Vietnam War, leading to MEP equipment procurement policies that established a streamlined family of standard generator sets. As described in this chapter, this standard family approach is now being abandoned in the process of establishing a new MEP equipment procurement policy for the next generation of acquisitions. Complex tradeoffs between such factors as initial acquisition costs and equipment supportability are extremely important in setting this policy.

Reliability and Availability

The importance of high reliability for individual MEP units is readily apparent. Specifications for the next generation of Army standard MEP generator sets calls for mean-time-between-failure (MTBF) characteristics of 600 hours. Reliability is closely coupled to the concept of equipment robustness, describing the ability of a generator set to withstand various forms of physical and environmental abuse without failure. Robustness requirements generally take the form of environmental and vibration specifications defining requirements such as operating temperature range.

Another related concept is power availability, describing the ability of the MEP equipment to supply electrical power in the presence of component failures, battle damage, or both. Power availability from MEP equipment in the field includes larger system design issues relating to electrical system networking and redundancy provisions in case of individual generator set losses. Nonsymmetrical power backup schemes combining, for example, a towed generator set with onboard vehicle power generation for backup power clearly enhances overall power availability and supportability (see Chapter 3, section on Networking).

Cost

In view of the large Army inventory of about 133,000 MEP units, the importance of power plant cost cannot be minimized. In particular, it should be emphasized that the most meaningful basis for evaluation of MEP equipment cost is life-cycle cost (LCC) rather than initial acquisition cost alone. Fuel costs over the lifetime of an MEP generator set typically exceed the initial acquisition cost by large percentages. Thus, power plant efficiency deserves a significant role in preparing cost evaluations. However, past Army experience indicates that LCC is given very little weight in MEP generator set procurement decisions compared to the initial equipment acquisition costs.

Other major factors influencing MEP equipment costs include standardization and commercial acquisition policies, addressed later in this chapter. Decreases in the defense budget ensure that cost will play a dominant role at every stage in setting the manner and timing by which the Army will proceed to replace its aging MEP generator set inventory. Great care and ingenuity will be necessary to achieve the proper balance between these very real budget constraints and the escalating performance demands imposed by Army 21 requirements.

PRESENT ARMY MEP ACQUISITION POLICIES

This section briefly summarizes key themes that dominate current Army MEP generator set acquisition plans. It is worth noting that there have been no Army generator set acquisitions from Fiscal Year 1985 (FY85) through FY87, with present plans calling for reinitiated acquisitions during FY88. Plans are now well underway for the next round of MEP equipment acquisition according to the Generator Acquisition Management Execution (GAME) plan summarized in the following sections. Committee concerns regarding the impact of this plan on future Army MEP inventories are discussed later in this chapter under "Issues."

Standardization

For the past 20 years, the Army has carried out an aggressive program of generator fleet standardization, reducing the number of different makes and models from over 2,000 in 1967 to only 117 at present. Supporting parts were reduced from 3 million to 161,000 in the process. Equipment field supportability has been significantly enhanced as a result of this standardization. The principal means of accomplishing this improved standardization has been through establishment of a standard family of MEP generator sets that includes fewer than 30 models.

In addition to parts inventory reduction and field supportability improvements, standardization provides advantages in terms of battlefield vulnerability. In particular, the use of standard generator sets makes it more difficult for an enemy to positively identify the nature of a detected target if the generator set family signature is standardized. However, standardization by itself is no substitute for signature suppression as enemy weapons in Army 21 battlefields become increasingly "smart," signature-sensitive, and lethal.

Although the advantages of such standardization cannot be disputed, the military standard-family generator sets are inevitably penalized by higher production costs because of their specialized designs and limited volumes. As described below, the Army is now implementing an alternative acquisition strategy to take greater advantage of commercial generator set production volumes: this will reduce acquisition costs. Carrying out this commercially-oriented acquisition policy in a manner that does not sacrifice supportability or field performance poses a major challenge.

Commercial Nondevelopment Item (NDI)-Based Acquisition Strategy

The Army has undertaken a multiyear program to replace over 80 percent of its current inventory of MEP generator sets during the period FY88 through FY93. This major inventory overhaul is to be accomplished according to a defined GAME plan, with key production award decisions scheduled for early 1988. Since scheduled initial production awards predate the release date for the present report, the committee recognized from the outset that the results of its work would not be available in time to influence initial GAME plan procurements.

Although no award decisions under the GAME plan have been made at present, a major thrust in the evolving acquisition policy is to increase the use of commercial NDI (nondevelopment item) generator sets. The objective of this strategy is to significantly reduce acquisition costs by procuring generator sets based on commercial practices, with MIL-STD requirements introduced only where necessary. Consistent with this strategy, a new set of generator equipment specifications (CGSA--Commercial Generator Sets & Assemblies) have been defined: these are claimed to cover 98 percent of the total Army generator set requirements (Table 2-3). These CGSA specifications are intended to include nearly all battlefield MEP units with power ratings of 10 kW or under, making very limited provisions for Army 21 battlefield conditions.

By basing the new Commercial Generator Sets and Assemblies specifications on existing commercial practices, the need for special development programs to meet these new "low" requirements is practically eliminated (Note that the term "low" refers to performance requirements). A separate set of "high" requirements has been defined (Signature-Suppressed Diesel Engine Driven, SSDED) to provide low-signature MEP units for the limited number (about 3,000) of nuclear delivery and air defense artillery systems (Table 2-3). All of these SSDED units are large generator sets in the range of 15 to 100 kW rather than the smaller sets that dominate Army 21 battlefield needs. The Army's objective is to limit the amount of special development engineering required for these SSDED units as much as possible to minimize initial acquisition costs.

Predominance of Towed Power

The existing fleet of Army MEP generator sets consists almost entirely of skid- and trailer-mounted units. The number of available VED and man-portable MEP units is very low. The strategy for the new GAME plan will change this mix very little. For example, anticipated opportunities for VED power during the next five years comprise 800 units in the range of 3 to 5 kW, accounting for about 0.5 percent of the total Army generator set inventory. There are no plans to pursue a broader policy of requiring VED power units as standard accessories in future procurements of the General Motors High Mobility Multipurpose Wheeled Vehicle (HMMWV), the Commercial Utility Cargo Vehicle (CUCV), or the Medium Tactical Vehicle Family (the trucks).

Summary

The present GAME plan provides a strategy for replacing the aging fleet of Army MEP generator sets within reduced defense budget allocations. It proposes to accomplish this feat by eliminating engineering development expenses almost completely and, depending on the worldwide commercial generator manufacturing base, to minimize per-unit acquisition costs. The new policy makes very little provision for man-portable or VED power units in future procurements. The extent to which this NDI-based acquisition strategy is capable of satisfying specialized Army MEP needs with minimum parts inventories is an issue of concern as discussed below.

TABLE 2-3 Current Fleet vs Commercial Generator Sets and Assemblies, Required Operational Capability (CGSA ROC) and Signature-Suppressed Diesel Engine Driven (SSDED)

	Current Fleet Performance	SSDED ROC Requirements	CGSA ROC Requirements
Aural Signature	79-85 dBA @ 25 ft	Non Detectable @ 300M	70 dBA @ 7 M
Fuel	Gas/DSL/JP4[e]	DSL/JP4	Diesel
Environmental	All Climatic Conditions	All Climatic Conditions	3 of 4 Climatic Conditions
Power (kW)	1.5-200	15-100	3-100
Frequency (Hertz)	DC/50/60/400	50/60/400	60
HAEMP[a]	No	Yes	Yes
Nuclear Hardening	No	Yes	No
Infrared Suppressed	W/Nets	$\pm 4^{o}C$	W/Nets
Reliability (MTBOMF)[b]	140-408	400	500/600
Standard Voltage Connections	Yes	Yes	Yes
STE/ICE (15 kW and larger)[c]	No	No	Yes
Slave Receptacle	Ordnance	Ordnance	NATO
Solderless Connections	Yes	Yes	Yes
Operable in MOPP IV[d]	Yes	Yes	Yes
Manportable (3 kW)	Yes	N/A	Yes
Paralleling (15 kW and larger)	Yes	Yes	Yes

[a] High altitude electromagnetic pulse.
[b] Meantime between operation and maintenance failure.
[c] STE (Standard test equipment); ICE (Internal combustion engine).
[d] MOPP (Mission oriented protective posture).
[e] Gas (gasoline); DSL (diesel)

ISSUES

Obstacles to Incorporating New Technology

It the battlefield threats described in Army 21 doctrine are indeed taken seriously, the Army cannot afford to depend on past solutions for meeting MEP system needs in future battle zones. Unfortunately, based on acquisition costs, current Army MEP acquisition policies are focussed on minimizing initial acquisition costs by depending on commercially-available equipment. As a result, opportunities for new technology to meet special MEP needs are being severely curtailed. Although the realities of defense budget cutbacks cannot be ignored, the current discretionary budget assigned to exploring promising new MEP technologies (less than $1 million during 1988 at Ft. Belvoir) is clearly insufficient to generate solutions to the problems posed by Army 21 battlefield conditions.

An additional obstacle that has impeded the introduction of advanced-technology MEP systems in the past is the process by which the Army identifies committed users of new equipment--the basis of issue (BOI) process. Without describing this BOI process in detail, it can be noted that BOI problems have a past history of prematurely halting advanced generator development programs because firm customers within the Army could not be identified, even when the technical results were very promising. The process of transferring new technology out of the laboratories and into production equipment is never an easy process, in the commercial world or in the military. The associated technical risks must be properly managed to avoid burdening any one potential user with too large a share, inviting rejection in favor of a safer, but less-satisfactory solution. As a result, special attention must be given to this transition process to ensure that significant new technology survives the critical early development stages.

Successful incorporation of new technology to meet future MEP system requirements requires much more than simply increasing the appropriate research, development, and engineering budget. Established policies, derived from one set of considerations, can pose formidable barriers to vital developments when such policies are blindly applied. For example, special care must be exercised to ensure that the policy of "one fuel on the battlefield," however well-considered, will not prevent the use of hydrogen-fueled fuel cells for man-portable power, if these are required for Army 21. Similarly, the quest for nondevelopmental procurement must not be allowed to completely displace innovative approaches in favor of marginal quick fixes. Opportunities for new systems to meet the special "high"-end needs of future battlefield MEP equipment must be preserved and expanded to meet Army 21 requirements.

Inadequacy of Past MEP Systems for Army 21 Battlefields

The principal shortcoming of present Army plans to rebuild its aging fleet of MEP generator systems is its failure to deal in any way with the

demanding implications of Army 21 doctrine for future battlefield conditions. If one accepts Army 21 concepts of enemy weapons that are increasingly "smart" and target-discriminatory, the inevitable conclusion is that high mobility and suppressed signatures are absolute requirements for survival on future battlefields. The existing GAME plan for 1988 to 1993 generator set procurement fails to adequately respond to either of these increasingly urgent requirements in the process of turning to an NDI-based policy to minimze initial acquisition costs. The negative impact of this NDI-based strategy on the supportability of future MEP units in the field is a source of serious concern to the committee. The critical nature of the front-line systems demands special attention to ensure their future supportability as well as survivability.

Two classes of Army MEP systems are identified earlier in this chapter--man-portable and vehicle-portable--along with various subclasses. There is very little evidence in current Army MEP procurement plans that the distinct roles and interrelationships among these three MEP system classes are recognized or exploited to advantage. For example, promising opportunities for VED power to provide enhanced electrical system mobility, supportability, and availability, in combination with conventional vehicle-transportable MEP units, are almost completely overlooked in current plans. Man-portable generator sets are specialized equipment, not well suited to a commercial-NDI acquisition strategy desired for new GAME plan procurements.

No single class or subclass of MEP systems defined earlier will be adequate to meet the Army 21 battlefield electrical system requirements. A coordinated systems approach to supplying mobile, quiet electrical power on future battlefields is a fundamental cornerstone not readily apparent in current Army MEP strategy.

CONCLUSIONS AND RECOMMENDATIONS

The committee reached the following conclusions and recommendations with regard to Army 21 and the needs of the Army for mobile electric power:

Conclusions

- The supply of electric power for the needs of Army 21 is of critical importance to the mission of the Army.
- It appears that high-performance mobile electric power is not considered essential to the Army's strategic thinking regarding Army 21. The continuation of current procurement practices and development policy will not result in a fleet of high-performance MEP units that meets the needs of Army 21. High-performance MEP units, capable of operating in combat situations, will require military research and development.
- To meet future battlefield requirements, the Army will need a family of high-performance MEP sets, that is, having low signature, high power density, and be easily transportable, not now commercially available, in addition to sets having less stringent performance characteristics.

o To date, the Army has not addressed and quantified the type, quality, and magnitude of MEP power requirements needed under the Army 21 scenario. This information would have helped the committee to make more specific recommendations.

Recommendations

o The Army should integrate the needs for mobile electric power supply, as dictated by the Army 21 scenario, into its overall strategic planning, especially for the Army 21 concept. This requires that a central authority be established having responsibilities for an overall development plan for how MEP technologies should be integrated into Army 21.

OVERVIEW OF REPORT

The present chapter provides an overview to the U.S. Army and its present and future needs for mobile electric power. Chapter 3 discusses the constraints and requirements for the MEP units, such as acoustic and infrared signature, and presents an introduction to the systems perspective needed to understand the tradeoffs if engine, alternator, power conditioning, and field use are considered as a system. Chapter 4 discusses future technologies for engines and power sources, electric technologies, and signature reduction. Based on its assessment of Army needs and the evolution of technologies, the committee recommends MEP technologies for consideration in Chapter 5. The Appendices present more technical detail for the various technologies.

3

SYSTEM CONSTRAINTS AND COMPONENT INTERACTIONS

This chapter introduces the requirements and constraints that mobile electric power (MEP) units must meet as well as introduces the systems perspective, the interactions among power source, alternator, and use, that are central to understanding the tradeoffs involved for different MEP technologies. The first section is a brief introduction to signature requirements. A discussion of fuels and the Army fuels policy follows. The characteristics of the different components are also introduced to understand the tradeoffs involved in the systems perspective.

SIGNATURE REQUIREMENTS

Aural Signature

Acoustical nondetectability limits have been suggested by the U.S. Army Human Engineering Laboratory for future U.S. Army generator sets (Garinther et al., 1987). The purpose of nondetectability limits is to ensure that an observer cannot distinguish the generator set noise from background sound.

Non-detectability is designated as either typical or critical. The critical nondetectability limit assumes a background noise level of a locale at least 16 km from a source of man-made noise. The typical limit assumes a background sound level of an environment at least 4 km from a man-made noise source. Typical and critical nondetectability limits are expressed as maximum linear sound pressure levels allowed at one-third-octave center frequencies of 50 to 10,000 Hz.

Although partially driven by tightened European Economic Community (EEC) noise standards (Table 3-1), the nondetectability limit presents a more complex requirement than dB(A) regulation of commercial applications. Community noise limits do not specify frequency content, only the summed spectral value, usually expressed as an "A-weighted" decibel (dB[A]) limit.

Army 21's emphasis on signature suppression will likely require aural nondetectability for power generators in a combat zone. In non-combat areas, power generator aural signature is less important. However, mobile electric power (MEP) used in support areas still must comply with EEC and similar community noise standards.

TABLE 3-1 Regulation of Power Generator Noise, European Economic Community (EEC) Standard (84/536)

kW Output	Current Standard		1990 Standard	
	ESPL @ 10 M* (dB(A))	Sound Power (dB(A))	ESPL @ 10 M[a] (dB(A))	Sound Power (dB(A))
< 2	73	104	71	102
2 - 8	73	104	69	100
8 - 240	72	103	69	100
> 240	74	105	69	100

[a] ESPL = Equivalent Sound Pressure Level

Non-detectability spectrums differ for each combination of (1) nondetectability distance (distance from noise source to observer) and (2) measurement distance (distance from noise source to microphone, for test purposes). A 300 m nondetectability distance has been suggested by the U.S. Army Human Engineering Laboratory as a reasonable development goal for most power generators (Garinther et al., 1987; School, 1987).

A 10 m measurement distance from microphone to the power generator is compatible with noise test facilities of many engine and generator manufacturers. Subsequent references to either a typical or a critical nondetectability limit assume a 300 m (nondetectability) and 10 m (measurement) combination (Figure 3-1).

Infrared Signature

Infrared (IR) sensors are of great importance in the detection, tracking and targeting of heat sources. Such detectors currently equip many missiles, combat helicopters and fighting vehicles, and in future small man-portable forward-looking infrared imaging (FLIR) units for individual infantrymen may be expected. While performance and resolution of individual types of detectors are classified, it suffices to say that bright, unresolved sources can be detected below the limit of resolution of the optical system, which operates monochromatically at wavelengths with low atmospheric absorption. Wavelengths chosen are not absorbed or emitted by water vapor and carbon dioxide, the major atmospheric IR-active gases, but they are dispersed and refracted by colloidal matter in the atmosphere, such as water droplets and dust particles. This can limit target detectability under some conditions.

A second aspect of the necessary choice of active wavelengths is that hot exhaust plumes (consisting of radiating water vapor and carbon dioxide) can normally not be detected, except at very short distances, since their emitted signal is rapidly absorbed on passing through the atmosphere. Thus, tactical equipment designers should only be concerned with the shielding of parts that are hotter than the rest of the device, and they should pay attention to solar heating of exposed metal and other components, and to solar glint from reflecting surfaces. The latter may have low visible reflectivity, but this does not necessarily mean IR reflectivity is low. Examples of the latter may be surfaces with dark-colored paint finishes. Note that a hot painted object is more visible than a hot unpainted object since a low reflectivity surface may have high emissivity.

Total radiation from black bodies follows the Stefan-Boltzmann law, and is proportional to T^4, where T, in degrees K, is the absolute temperature of the source. The limits of detectability are therefore given by the ability of the sensor to see the contrast between the signal and the background. For some targets, for example, an aircraft seen against the sky, the contrast is very high, whereas for relatively cool objects seen against a natural background of vegetation, it can be quite low. In general, state-of-the-art sensors can detect resolved objects with temperature differences of about 2 K above ambient, that is, a resolution against background of $[(300)^4-(298)^4]/(300)^4$, or 2.6 percent. Under some conditions, they can be better than 2 K.

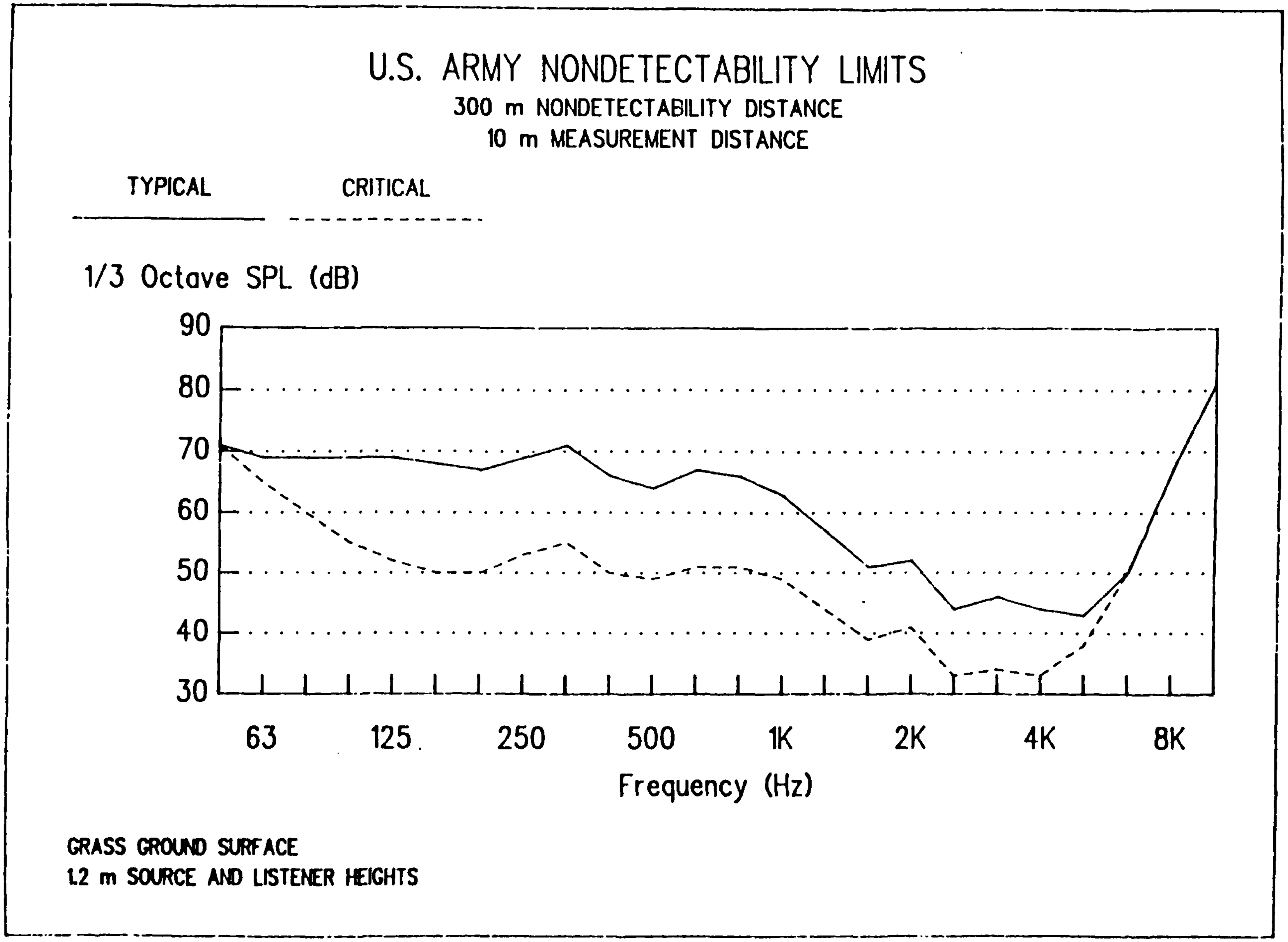


FIGURE 3-1 U.S. Army nondetectability limits. Sound pressure level (SPL) in decibels (dB).

It is generally conceded that the design of tactical equipment for which no part is 2 K above ambient is impractical (Shields, 1987), especially if the equipment must contain hot parts such as exhaust systems. Mobile power sources for tactical use in high sensitivity applications are therefore not zero-signature, but are rather low-signature, defined as having no IR-observable parts greater than 4 K above background (that is, a 5.2 percent radiation increase over ambient).

Electromagnetic Signature

An electromagnetic (EM) signature is caused by emissions that are detectable by sensors that are essentially radio receivers. The MEP systems that are presently in use produce very little EM signature while the equipment that uses the electric power often produces very large amounts of EM radiation. As in the cases of acoustical and infrared signatures, detectability is a function of the ability to distinguish a particular signal pattern in a very "dirty" background.

An EM signature is produced by radiated EM energy, the same process that is used for wireless electronic communication. The ideally balanced MEP system will have no emitted EM energy. Since the ideal system does not exist, there are very low magnitude harmonic emissions at frequencies of 50 to 60, 100 to 120, and 150 to 180 Hz. Higher harmonic components are nearly completely suppressed in properly designed alternators, and MEP specifications demand this class of effective harmonic attenuation. There will be, however, significant high frequency emissions from an alternator or distribution system that contains discontinuities (broken windings or loose connections). Commercial test equipment is used to detect these emissions as an indication of the need to perform maintenance or repair.

The equipment that utilizes the electric power (loads) is often a source of very high magnitude EM emissions. Equipment such as radio transmitters, and electronic countermeasures devices (ECM) are designed for the sole purpose of radiated EM energy. In addition, such mundane equipment as electric typewriters, fluorescent lights and thermostatically controlled coffee urns emit higher levels of EM radiation than the MEP sets. An EM signature is the easiest of the three signatures to detect since the detection technology is the most advanced. In addition, the very low frequencies emitted by MEP sets are the least attenuated by natural attenuators such as vegetation, hills, buildings, etc. Ease of detectability and low attenuation means that every source of low frequency electromagnetic radiation is detected, and it is nearly impossible to pinpoint a specific source. Therefore, the low frequency, low magnitude emissions from MEP sets do not create a practical signature problem.

FUELS REQUIREMENTS AND CONSTRAINTS

Background

Any discussion of fuels for MEP should begin with an understanding of the boundary conditions imposed by two relevant initiatives that were put in

place by the Department of Defense (DoD). In the late 1950s the Army decidad to convert most of its mobility equipment from spark ignition (SI) to diesel engines (Bowden et al., 1986). Presently this conversion is essentially completed and, except for administrative equipment and generator sets of 10 kW and less, which are still SI engine powered, the Army has become "Dieselized". The second initiative, "A Single Fuel on the Battlefield", was adopted in 1986 in response to the conversion within the North Atlantic Treaty Organization (NATO) from JP-4 to JP-8 fuel for all aircraft. The single fuel on the battlefield initiative requires the use of JP-8 (MIL-T-83133) for both aircraft and ground equipment (BRDEC, 1987). This initiative does not apply within CONUS (continental United States) where JP-4 (MIL-T-5624) and DF-2 (VV-F-800) will continue to be used as gas turbine and diesel engine fuels for all operations. Some of the property requirements for DF-2, JP-4 and JP-8 may be compared by examining Table 3-2.

The broad implication of these two initiatives is that all future internal combustion engine (ICE) powered mobility equipment must possess the capability to operate on distillate fuels in the boiling range of kerosene and higher. Since this tends to rule out gasoline-fueled engines, and since the Army fleet of generators is now 80 percent fueled by gasoline (Bramlette, 1987), in the near future the diesel engine will necessarily be used much more extensively for MEP than it is at present. In the longer term, perhaps other engines currently under development may emerge to displace the diesel engine but at present there seems to be no other nondevelopment item (NDI) available.

Future Fuel Considerations

During the next 30 yrs, liquid fuels will in all probability be the dominant energy source for military mobility equipment. Petroleum crude oil, with perhaps the gradual introduction of various syncrude oil, will provide the feedstocks from which these fuels will be refined (Kane, 1980). Evidence indicates that the quality of petroleum crude oil worldwide is declining as is also the quality of the product slate (Bowden et al., 1986; Belardini et al., 1985). Therefore, future production of distillate fuels with current specifications will require more extensive treatment and refining of the available feedstocks. It is likely, then, that fuel specifications will broaden over time for two primary reasons. First, to extend crude oil supplies, more of the high boiling point heavy parts of the barrel will be used and second, the quality of available crude feedstocks will place practical and economic limitations upon the extent of the processing. Future diesel engine fuels will gradually get heavier, a process that appears to have already begun (Dickson and Woodward, 1986).

The challenge faced by refiners is to match the production of fuels to the product demand (Figure 3-2 and Coley et al., 1986). The solution lies in additional process conversion. This does increase the yield of transportation fuels but the ignition quality of the resulting distillate fuel is poorer than those obtained from atmospheric distillation. The use of more cracked products in diesel engine fuels reduces their quality (Coley et al., 1986).

TABLE 3-2 Comparative Requirements of Diesel and Turbine Fuels

Properties	VV-F-800C DF-A	VV-F-800C DF-2	MIL-T-5624-L JP-4	MIL-T 83133A JP-8
Flash Point, °C, min	38	52	NR[b]	38
Cloud Point, °C, max	-51	[a]	NR	NR
Pour Point, °C	Rpt	Rpt	NR	NR
Freezing Point, °C, max	NR	NR	-58	-50
Kinematic Viscosity at 40°C, cSt	1.1 to 2.4	1.9 to 4.1	NR	NR
Kinematic Viscosity at -20°C, cSt, max	NR	NR	Rpt	8.0
Distillation, °C				
10 percent recovered, max	NR	NR	Rpt	205
20 percent recovered, max	NR	NR	145	Rpt
50 percent recovered, max	Rpt	Rpt	190	Rpt
90 percent recovered, max	288	338	245	Rpt
End Point, max	300	370	270	300
Residue, vol percent, max	3	3	1.5	1.5
Sulfur, mass percent, max	0.25	0.50	0.4	0.3
Cu Corrosivity				
3 hrs at 50°C, max	3	3	NR	NR
2 hrs at 100°C, max	NR	NR	1B	1B
Ash, wt percent, max	0.01	0.01	NR	NR
Accelerated Stability, mg/100 mL, max	1.5	1.5	NR	NR
Neutralization Number, mg KOH/g, max	0.05	NR	0.015	0.015
Particulate Contamination, mg/L, max	10	10	1.0	1.0
Cetane Number, min	40	40	NR	NR

[a] Specified according to anticipated low ambient temperature at use location.
[b] NR = No requirements.
Rpt = Reported

SOURCE: Military Handbook Mobility Fuels User Handbook, MIL-HDBK-114, 16 January 1984.

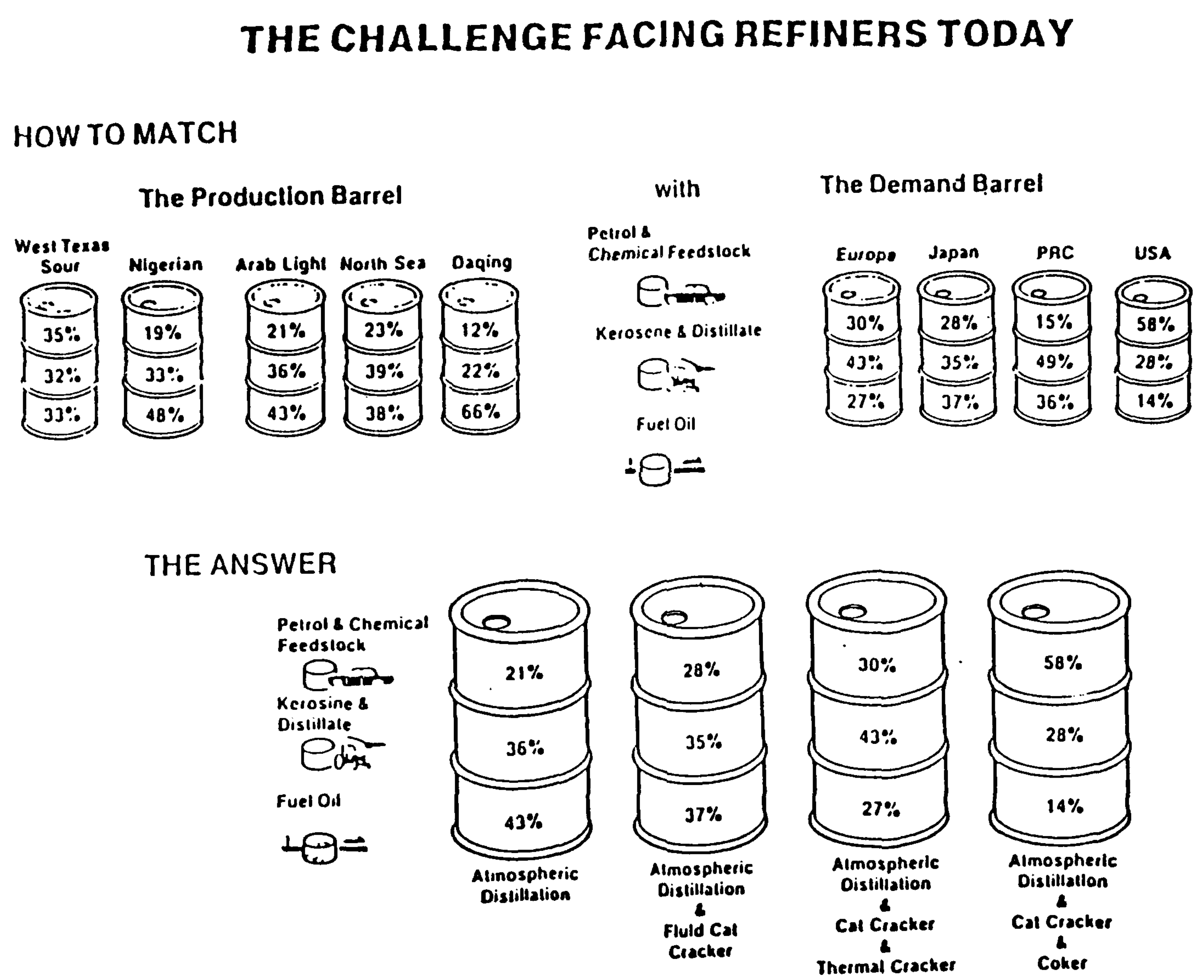


FIGURE 3-2 The challenge facing refiners regarding production and demand of petroleum products.

SOURCE: Coley et al. (1986).

Fuel properties that affect diesel engine performance are energy content, ignition quality, viscosity, volatility, aromatic content and impurities. All of these properties are related to the refinery feedstock and the way it is processed to produce the finished fuel. The power output of an engine is governed by the energy content of the fuel and the combustion process that releases this energy. While energy content per unit volume usually increases as the specific gravity of the finished fuel increases, the positive effect on engine performance caused by this is generally more than offset by attendant adverse combustion effects (Coley et al., 1986; Obert, 1973). As diesel engine fuels get heavier, viscosity and impurities increase while volatility and ignition quality decrease, all of which tend to deteriorate the diesel engine combustion process (Coley et al., 1986; Obert, 1973; Montemayor et al., 1985). These fuel properties influence the combustion process mainly by controlling its initiation and rate.

The initiation of an effort directed toward the development of suitable referee fuels was prompted by the Army's realization that future engine developers would require guidance with regard to restrictions that future fuels may impose. These represent a best estimate as to the extreme property limits of future fuels (Table 3-3). Referee fuels are used by the Army during the research, development, and proof testing of new engines to ensure satisfactory performance when they are put into field use. This effort began in 1981 and was based on the premise that future Army engine systems would have a multifuel capability defined by the developed referee fuels. Further, it was assumed that a single referee fuel could not provide a wide enough property range for multifuel engine development and, therefore, two referee fuels were proposed (Bowden et al., 1986). Figure 3-3 depicts the extremes of fuel tolerance that might be anticipated for future multifuel engines (Bowden et al., 1986). To date, the requirements for the high volatility Type I and the low volatility Type II near-term referee fuels have been established and promulgated in military specification MIL-F-53080 (1988) (see Table 3-3 for properties). The adoption of these fuels is fully supported by both the U.S. Tank Automotive Command and the Office of Mobile Power at Ft. Belvoir (Bowden et al., 1986).

It is of interest to note that both Figure 3-3 and the Army Mobility Fuels Scenario (Stavinoha, 1987) include oxygenated fuels, in particular methanol. There are several factors that seem to prevent the use of methanol for MEP purposes. Among these are the single fuel on the battlefield directive, safety, and energy density. Of these, the last perhaps is the most difficult to overcome. The energy density of methanol is approximately one half that of distillate fuels. Thus, the mass of methanol required for any mission would be twice that of the required distillate fuel and would aggravate fuel logistics of storage and on-board transportation.

Summary

In summary then,

1. Army engines will have to burn JP-8.
2. Liquid distillate fuels derived from petroleum and various syncrudes will continue to be used through the near and midterms.

TABLE 3-3 Requirements for Experimental Referee Grade Fuels

Property	Type I Requirements	Type II Requirements
Reid Vapor Pressure, kPa	6.9 to 34.5	NR[a]
(psi)	(1 to 5)	NR
Density at 15°C, kg/L	0.750 to 0.801	0.934 max
Gravity, °API	45 to 57	20 min
Distillation, °C (°F)		
10 percent recovered	127 max (260 max)	report
50 percent recovered	NR	
50 percent recovered	191 max (375 max)	report
90 percent recovered	232 max (450 max)	report
End Point	288 max (550 max)	316 to 385 (600 to 725)
Cetane Number	20 to 30	35 max
Flash point, °C (°F)	NR	54 min (130 min)
Carbon residue on 10 percent bottoms, mass percent	0.20 max	0.40 max
Kinematic Viscosity at 40°C (104°F), cSt	0.9 max	7.0 to 9.0
Sulfur, mass percent	0.5 max	0.80 to 1.20[b]
Ash, mass percent	0.01 max	0.05 max
Cloud point, °C (°F)	NR	-7 (+20)
Freezing point, °C (°F)	-40 max (-40 max)	NR
Thermal stability		
JFTOT at 260 °C (500°F)		NR
Pressure drop, in. Hg	25 max	NR
Tube rating	3	NR
Hydrogen, mass percent	report	NR
Particulate contaminants, mg/L	10 max	10 max
Accelerated stability, mg/100 mL	NR	1.5 max
Copper corrosion at 50°C (122°F)	1 max	1 max

[a] NR = No Requirement

[b] = Naturally occurring sulfur is preferred, but addition of Tert-butyl disulfide is permitted. Not less than half of the total sulfur in the finished fuel shall be naturally occurring.

SOURCE: Bowden et al. (1986).

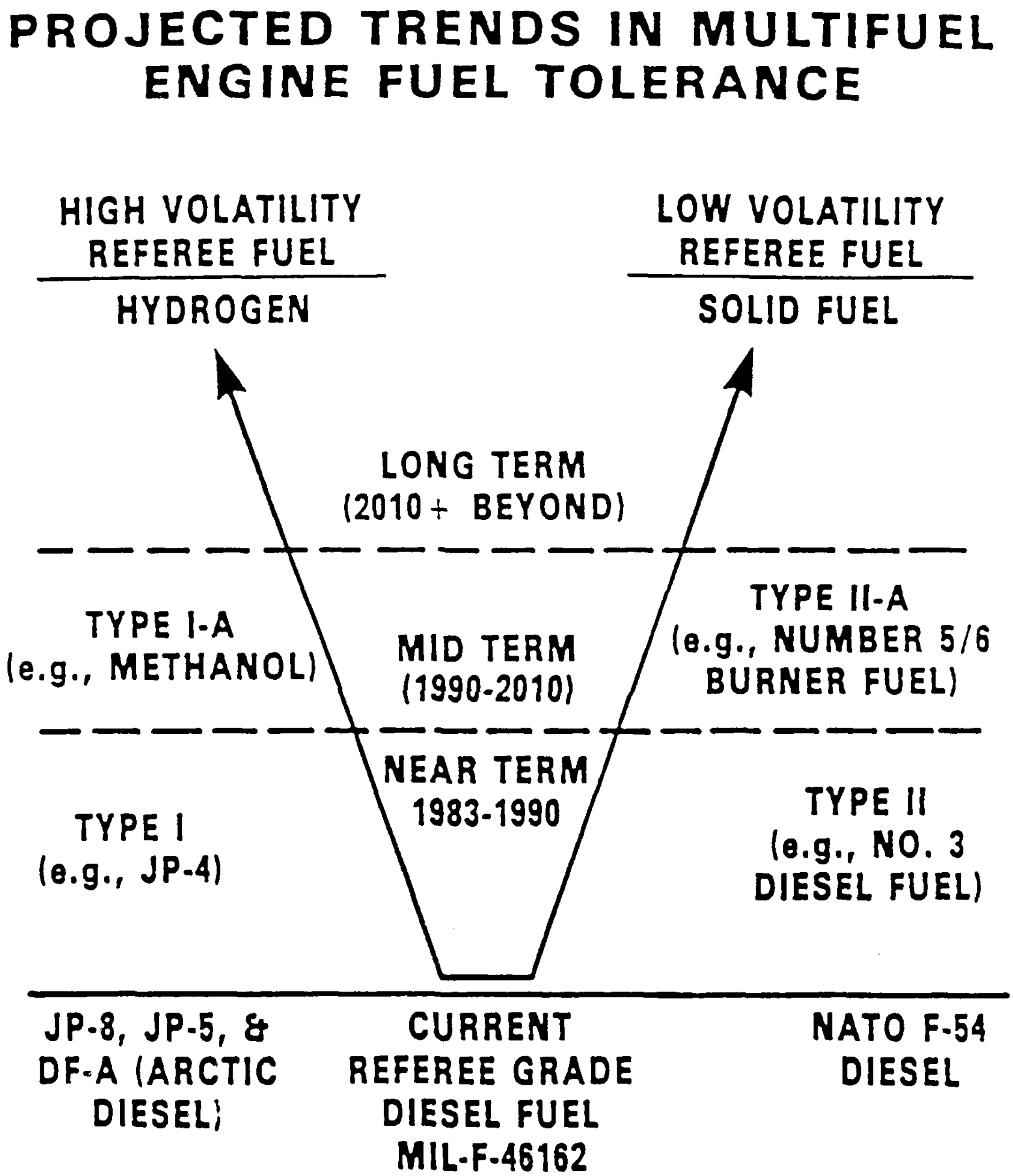


FIGURE 3-3 Projected trends in multifuel engine fuel tolerance.

SOURCE: Bowden et al. (1986).

3. The specifications of future fuels will be broadened and future engines should be designed to burn these future fuels.

COMPONENT AND SUBSYSTEM INTERACTIONS

Engines and Direct Converters

Current MEP units consist of an engine that converts fuel energy to mechanical energy and, using a generator, converts this mechanical energy to electrical energy. Thus, unless a gear box is used, engine speed determines generator speed which, in turn, affects generator size. However, as discussed later in the section on Power Conditioning, power conditioning is required for 60 cycle generation at speeds above 3,600 rpm. Furthermore, since the efficiency of the generator is relatively high, engine efficiency is a major factor in system efficiency and fuel consumption.

There are major differences in maximum engine speeds. Maximum gas turbine speeds are in the tens of thousands of rpm. Reciprocating engine speeds are usually not limited by rotational speed but by piston speed, that is, the average distance travelled by the piston in a unit time. For the same piston speed, smaller size engines, having a shorter piston stroke, usually run at higher rpm than do large engines. For an ideal reciprocating engine having the same power output, same piston speed and a bore-to-stroke ratio of unity, the required displacement will be inversely related to engine rpm, that is, twice the speed will halve the required displacement.

While not obvious from the above, the required number of cylinders will increase. If bore is linearly related to engine weight, the engine weight would ideally be halved for twice the engine rpm. In practice, as shown in Figure 3-4, the curve becomes non-linear at smaller bores because of minimum wall thickness required for the casting process and other factors. Thus, the weight will not be halved, particularly for small bore engines.

For diesel engines, high pressure injection introduces fuel into the cylinder late in the compression process, giving only milliseconds of time for introduction, distribution, vaporization, mixing and combustion. Because of the short time available, the maximum speed of most diesels, even of small size, has been in the 3,000 to 3,600 rpm range, although recent announcement was made of a 4,800 rpm diesel outboard engine. The diesel engine is a stratified-charge engine in which the fuel is distributed, initially at least, through only a portion of the combustion chamber air at part load. In stratified-charge engines, load control is exclusively controlled by varying the quantity of fuel with the quantity of air remaining constant. Consequently, the fraction of air where the fuel is distributed varies with load. Other examples of engines using the stratified-charge concept would be the Texaco Controlled Combustion Process (TCCS) (Mitchell and Alperstein, 1973) and the stratified-charge rotary engine (Mount et al., 1987). For thermodynamic reasons, stratified-charge engines have a smaller decrease in efficiency as load is decreased than do engines using a homogeneous charge plus throttling of

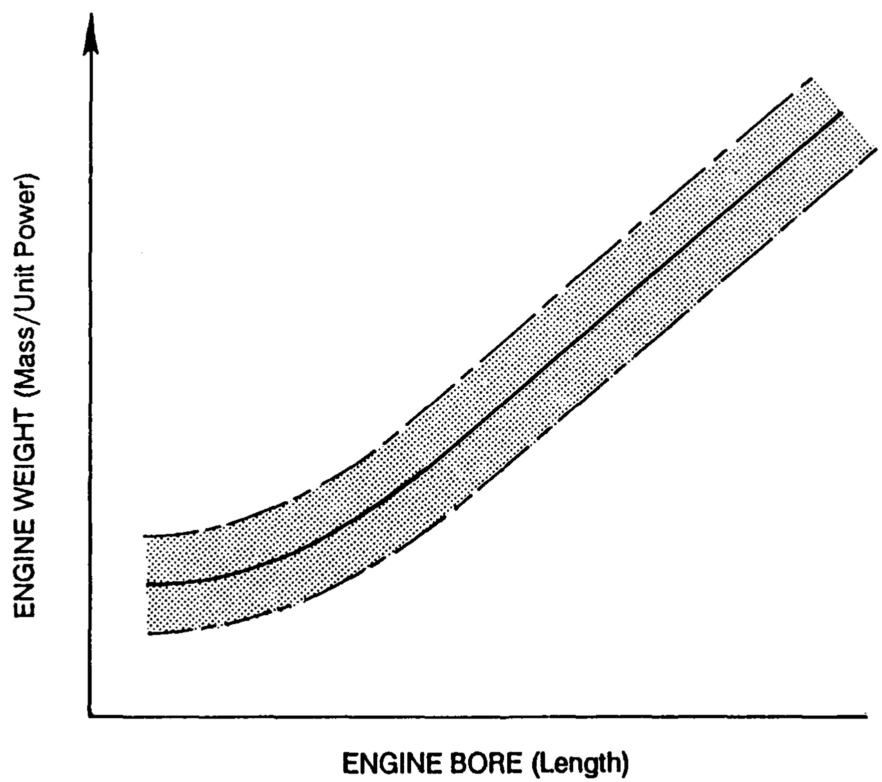


FIGURE 3-4 Qualitative relationship between mass per unit power and engine bore.

the incoming air-fuel mixture for load control. All stratified-charge engines except the diesel use some ignition source other than the temperature of compression, typically a spark.

Engines that introduce the fuel during the intake stroke (automobile engines, for example) have a longer time for fuel mixture preparation and consequently have a more nearly homogeneous mixture. Load control is achieved primarily by throttling of the incoming mixture. Since homogeneous-charge engines are limited more by piston speed than by the introduction, preparation, and combustion of the fuel, very small engines of this type operate at speeds up to 15,000 to 20,000 rpm (model aircraft engines, for example). The above discussions also apply to rotary engines which, because of their mechanical arrangement, usually have significantly higher output shaft speed than does a comparable reciprocating engine.

In summary, in smaller size MEP units, speeds of 3,600 rpm would be the most common with this speed being set partly by engine speed limitations and partly because power conditioning is required at speeds greater than 3,600 rpm. However, speeds up to twice that value can be readily achieved using rotary and homogeneous-charge engines and gas turbine speeds will be significantly higher, in the 20,000 to 50,000 rpm range.

Generator sets experience variable loads. Figure 3-5 is presented to show a typical distribution of operating time versus load for a 60 kW MEP unit. Note that a major portion of operation time is at half load or below. This is partially the result of the high power quality requirements and the consequent oversizing of equipment. With this notion of variable load in mind, note that engines differ in their decrease in efficiency as load is decreased. The efficiency of a non-regenerative gas turbine (gas turbines below 50 kW would generally be non-regenerative) decreases very rapidly with decreased load. A throttle-controlled, homogeneous-charge engine will show significant efficiency decreases with load but considerably less than a non-regenerative gas turbine. Stratified-charge engines suffer relatively small decreases in efficiency as load is decreased.

The ability to form a family of engines is important for MEPs because of the wide range of power covered by generator sets and the inherent savings on acquisition and logistic costs by commonality of parts in a family of engines. Again, engines differ in the cost of forming a family of engines. In a reciprocating or rotary engine, power can be readily doubled by adding a second cylinder or rotor, and so on. However, in a gas turbine a new design is normally required for significant changes in power.

Engines also differ in the way in which efficiency changes with engine size (power). The efficiency of intermittent-combustion engines decreases only slightly as engine size decreases. However, simple-cycle gas turbines, because of increased flow losses, experience significant decreases in fuel economy as size decreases. Currently, regeneration is not used on very small (about 50 kW) turbines (the 75 kW experimental automotive gas turbine is regenerative), which further decreases efficiency.

Currently, the only direct energy conversion units that can use JP-8 as a fuel are thermal-to-electric conversion devices. While they are quiet, their power density and efficiency are low, their cost is high and they

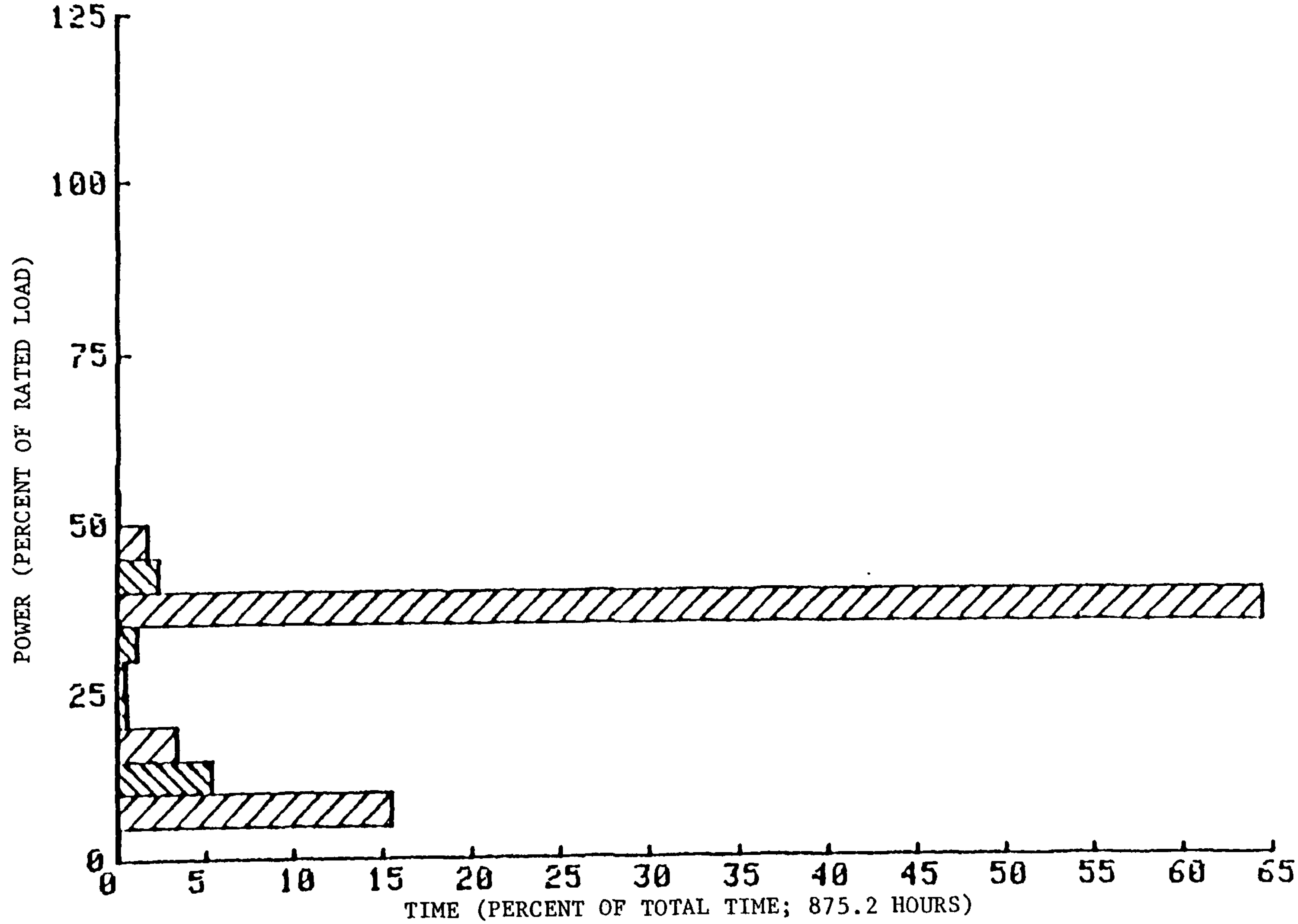


FIGURE 3-5 Percent of rated power vs. utilization time for a 60 kW generator set.

SOURCE: MERADCOM (1985)

are not available commercially. The same comment is applicable if the thermal-to-electric devices use nuclear power as a heat source. Current fuel cells cannot use JP-8 as a fuel (see Chapter 4).

Alternators

The electrical alternator is the component that converts mechanical energy supplied by the engine into electrical energy in the form of alternating voltage and current. The basic requirements for an alternator are: (1) a source of magnetic flux; (2) a coil of wire for generating the voltage (called the armature); and (3) a means of causing one to rotate with respect to the other.

Since the electrical output power of the alternator is much greater than the power needed to generate the excitation magnetic flux, MEP alternators are designed such that the armature windings are stationary with a rotating excitation flux source. The electrical output power is generated in the stationary part of the alternator (stator) where it is easy to collect and connect to the load, while the much smaller excitation power (in the case of electromagnet excitation) must be fed to the rotor of the alternator. Although this excitation power can be fed through sliding contacts or brushes, a small auxiliary alternator can be mounted on the rotor shaft to provide excitation, eliminating the need for brushes. This brushless excitation approach is strongly preferred for Army MEP equipment to minimize maintenance requirements. During steady-state operation, a small fraction of the output power is rectified and used to supply the excitation power.

The output frequency of the alternating current (ac) waveforms produced by the alternator is directly proportional to the rotor speed. In addition, the alternator can be designed so that there is more than one North and one South pole along the periphery of the rotor electromagnet. As a result, the output frequency is also proportional to the number of alternator pole pairs so that $f = n \times p / 60$, where f is the alternator output frequency in Hz, n is the rotor speed in rpm, and p is the number of alternator pole-pairs. Thus, an alternator with a single pole-pair must rotate at 3,600 rpm to generate 60 Hz. If the alternator is designed with two-pole pairs, 60 Hz generation demands a rotor speed of 1,800 rpm.

As described in more detail in Appendix C, the weight and volume of an alternator is almost inversely proportional to the rotor speed for a given power rating. From this standpoint, it is desirable to increase the alternator speed as high as possible. Unfortunately, the speed-frequency relationship given in the preceding paragraph dictates that the maximum rotor speed for 60 Hz power generation is 3,600 rpm, requiring a two-pole rotor design. These conditions place severe constraints on the designers' efforts to minimize the size and weight of MEP alternators that must deliver 60 Hz power at their output terminals. The two-pole configuration used in many MEP alternators imposes additional constraints on the designer that are absent in machines with larger number of poles (deJong, 1976).

One of the degrees of freedom that a designer does retain is the relative dimensions of the alternator length and diameter. For a given

power rating and speed, the volume and weight of an alternator are relatively insensitive to whether the machine is designed long with a small diameter, or short with a large diameter. Although several factors tend to favor the longer rotor design for standard MEP generators, there are special applications that make the short "pancake" alternator design attractive. Such large-diameter alternators are candidates for vehicle-engine-driven (VED) MEP systems in which the alternator is mounted in-line with the engine driveshaft.

Other factors influencing alternator size and weight include requirements for output waveform quality and transient loading. High power quality requirements included in Military Standard (MIL-STD)-1332 (see Chapter 2) tend to increase the alternator size and weight. For example, MIL-STD-1332 requires that the alternators be capable of delivering twice their rated currents for motor starting with voltage dips no greater than 30 percent for "Precise" Class 1 power. This requirement dictates that the alternator have a low impedance characteristic, which causes the machine size to increase. Low harmonic content in the alternator output waveforms demanded by MIL-STD-1332 also favors a conservative machine design, which increases alternator size and weight.

MEP alternator weight is dominated by iron and copper. Copper is an excellent electrical conductor and is used for all of the machine windings. The iron used in all the rotor and stator structures shapes and concentrates the magnetic field while adding mechanical strength. Despite its weight, iron is the best material available for providing the required alternator magnetic characteristics in the absence of high-temperature, high-flux superconductors.

As mentioned earlier, excitation magnetic flux for an MEP alternator is developed by current flowing in electromagnet windings mounted on the rotor. Since the generated voltage is proportional to the excitation flux level, voltage regulation is achieved by controlling the current fed to the excitation windings. Voltage changes require as much as two seconds because the alternator magnetic circuit tends to oppose changes in the exciting electrical current. This long field time constant is one of the major factors limiting the transient response characteristics of the MEP generator set to transient loading conditions.

As an alternative to the use of electromagnet field windings on the rotor, permanent magnets can be mounted on the rotor to supply the excitation magnetic flux. The permanent magnet is attractive as a flux source because the flux is provided without any dissipative losses, yielding an improvement in alternator efficiency. However, the magnetic flux developed by the permanent magnets cannot be conveniently adjusted, making it much more difficult to directly regulate the output voltage generated at the alternator terminals. In practice, the voltage regulation function must be performed externally using a power conditioner when permanent magnet excitation is adopted.

Power Conditioning

Power conditioning serves the useful role of changing the waveshape, amplitude and frequency of the electrical power using electronic means.

As discussed later in this chapter, electronic power conditioning is not mandatory in MEP generating equipment, although it can provide important system benefits when properly applied. From the standpoint of input-to-output power relationships, any power conditioner serves in one of the four following capacities:

Input	Output	Type	Remarks
ac --->	dc	Rectifier	Required for most electronics equipment
dc --->	ac	Inverter	ac output can be variable-frequency
ac --->	ac	Converter	Converts amplitude, waveshape, and frequency
dc --->	dc	Converter	Converts voltage, current levels

where ac represents alternating current power, and dc represents direct current. The latter two "converter" classes above (ac-to-ac and dc-to-dc) are important when it is necessary to change voltage and current levels between the input and output, or to change electrical frequencies or waveshape, or both, in the case of the ac-to-ac converter.

Additional roles played by the power conditioner include improving (or "conditioning") the output power quality by filtering the power before it is applied to the load. The power conditioner can also serve the role of buffering the load against electrical transients in the input power, which would otherwise be applied directly to the loads. In the extreme, the power conditioner can be configured to include internal energy storage (for example, a battery) that will continue to supply power to the load even when the input power is temporarily disrupted. This special type of power conditioner is known as an uninterruptible power supply (UPS), and is very important for supplying sensitive loads such as digital computers, which cannot tolerate even very short power outages.

Desirable characteristics of power conditioners include high power conversion efficiency, low weight and volume, low acoustic and EM signatures, and high reliability and ruggedness. Properly applied, the introduction of the power conditioner makes it possible to achieve net improvements in the overall power system characteristics by, for example, substantially reducing the size of other components.

Switching power converters have been actively developed during the past several years providing means for accomplishing these objectives. These switching converters use power semiconductor devices that are digital in nature (Hoft, 1986), that is, each power switch at any time constant is either 'on', conducting current with ideally zero impedance, or 'off', blocking all current with infinite impedance. The effective output waveform can then be synthesized by switching the power devices between these two states at high frequencies while gradually varying the ratio of 'on' to 'off' times (that is, duty-cycle control). Switching power converters with efficiencies well over 90 percent are now available.

The invention of the silicon-controlled rectifier (SCR) in the 1950s launched modern power electronics by providing the fundamental building block needed to produce high power switching converters (Dewan and

Straughen, 1975). Very large SCRs have been developed during the past three decades controlling currents and voltages of thousands of amperes and volts, respectively, making it possible to build power conditioners rated to handle megawatts of electrical power. Such large converters are being installed at a variety of international sites for high-voltage dc utility power transmission. Smaller thyristors have found applications in a wide range of industrial and commercial applications extending from household light dimmers to large industrial adjustable-speed motor drives.

Meanwhile, there has been considerable international research and development (R & D) activity devoted to improved power semiconductor switching devices which, unlike the SCR, can be turned off as well as on from the gating terminal. New power device products such as large gate turn-off thyristors (GTOs) and bipolar junction power transistors have already eroded much of the market for conventional SCRs except for very high power ratings. These new power devices make it possible to reduce power conditioner size and weight while improving system performance by eliminating the need for bulky power commutation components.

The size of the power conditioner is directly influenced by the electrical current that the equipment must handle, and the voltage levels that must be internally sustained. The product of the current and voltage represents the power rating of the power conditioner. In general, the size of the power conditioner for a given power level will decrease if the voltage level is raised with an inversely proportional decrease in the current level. Low-voltage, high-current supplies tend to be largest since large conductors and device areas are necessary to conduct the high currents.

The impact of the input or output frequencies on power conditioner size is heavily influenced by the stringency of the filtering requirements, since filter components can add substantial volume and weight. The size of filtering components (capacitors and inductors) decrease roughly inversely with frequency, making it advantageous to increase these frequencies where practical (for example, 400 Hz vs. 60 Hz) for minimum size.

During the 1960s and the 1970s, the Army actively funded R & D work in power conditioning technologies, particularly through programs carried out by Ft. Belvoir. Despite technical successes achieved within these individual programs, power conditioners have not been integrated into the Army MEP equipment basic inventory. The combined performance characteristics of these past generations of power conditioners did not provide sufficiently compelling system advantages in terms of cost, weight, volume, or reliability to warrant their adoption. Recent Army funding for power conditioning has dropped to very low levels as part of general budget cutbacks for electric MEP technology development.

As will be described in Chapter 4, the 1980s have been marked by a series of major advances in power electronics technology significantly improving both power density and reliability. These technical advances, combined with growing needs for lightweight electric power generation to meet Army 21 mobility demands, are opening new possibilities for electronic power conditioners in Army MEP equipment. The nature of this role from a systems perspective is described later in this chapter.

Control Systems

Two types of engine-generator systems are being considered for small MEP sets (Figure 3-6). In the conventional generator arrangement (Figure 3-6a), an engine drives a generator either directly or through a gear box. Since the output frequency of the generator is directly proportional to the generator speed, it must rotate at a synchronous speed; for 60 Hz output, the speed must be 3,600 rpm for a two-pole generator, 1,800 rpm for a four-pole generator, 1,200 rpm for a six-pole generator, and so on.

In the generator with signal conditioning arrangement shown in Figure 3-6b, the engine also drives the generator either directly or through a gear box. However, the generator is designed with a large number of poles to produce a high frequency output--on the order of several hundred or thousand Hz. The output from the generator is then fed to a signal conditioner where it is converted to 60 Hz power. Because the generator power is not used directly, the exact frequency is not critical and hence the speed of the engine-generator can vary somewhat without affecting the frequency of the output. In particular, it is not necessary that the generator be driven at particular synchronous speeds and hence the system can be designed to allow the engine to be run at the most optimum speed.

The individual controls required for each element in the system (engine, generator, and signal conditioner) depend upon the details of the particular component; the system controls, however, are similar regardless of what components are used. For example, the engine controls would be different for a diesel engine, a spark-ignited, stratified-charge engine, and a gas turbine but the overall system control concept would be the same.

Consider first the conventional system in steady-state operation where the electrical demand is constant. Under these conditions, the power produced by the generator is equal to the electrical demand, the power produced by the engine is equal to the electrical demand plus the generator losses, and the fuel input to the engine is whatever is required to produce the required engine power. The generator will be rotating at the design speed (assume 1,800 rpm for this example). The magnetic excitation in the generator will be adjusted to produce the required output voltage (assume 110 volts for this example).

Now assume the electrical demand is increased by switching on additional load. This increased demand occurs so rapidly as compared to the rate of response of the rest of the system that it can be considered to be instantaneous. When the electrical demand increases, it immediately increases the power required to drive the generator. The engine, however, cannot increase its power output instantaneously. The only appreciable amount of stored energy in the system is the kinetic energy of the rotating parts of the engine, the shaft, and the generator. Because the power output from the generator momentarily exceeds the power input from the engine, the excess must come from this kinetic energy and therefore the engine and generator start to slow down. As the generator speed drops below 1,800 rpm, the output frequency drops below 60 Hz (In addition, the voltage will decrease but this is an internal generator control problem.). In the conventional system, the engine governor senses the drop in speed and increases the fuel supplied to the engine. The

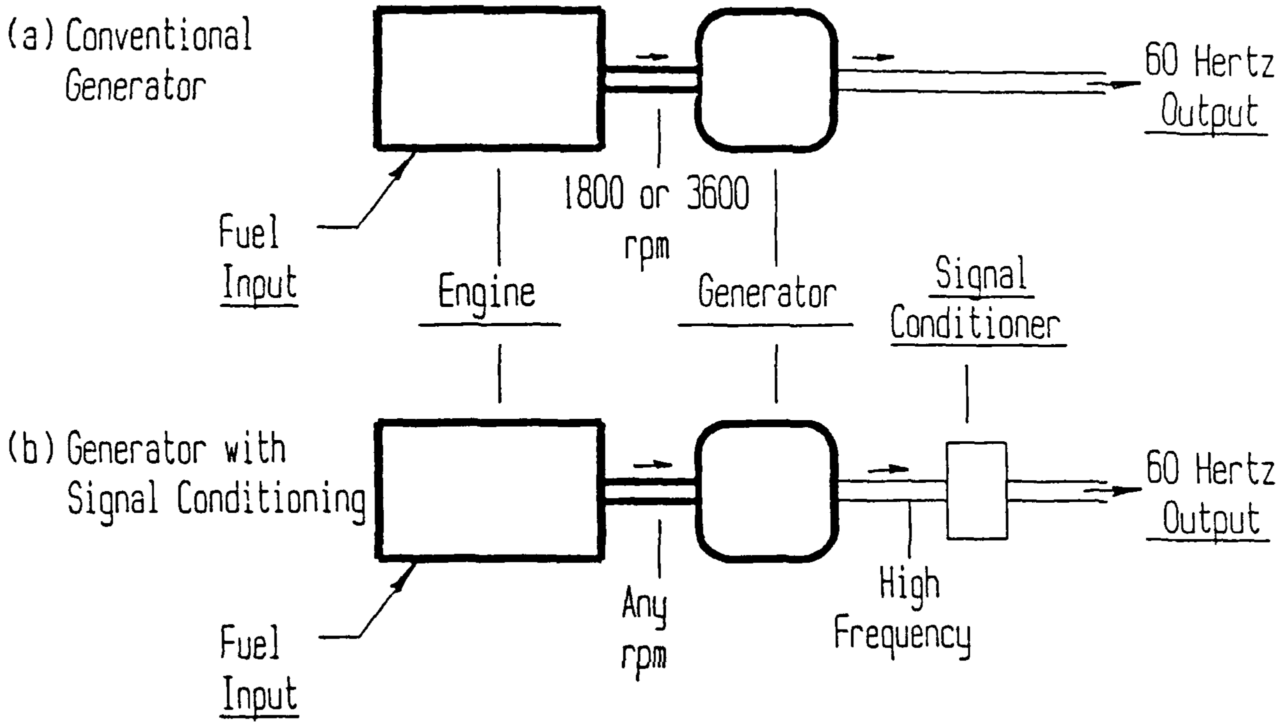


FIGURE 3-6 Block diagram of conventional generator and generator with signal conditioning.

increased fuel, in turn, increases the power output of the engine and equilibrium conditions are once again established.

In any conventional engine generator, some speed and frequency drop will occur when the electrical load is increased. It can be minimized by excess power capability in the engine; large rotating inertia in engine and generator; and more complex governing controls. There is, thus, a very real tradeoff between allowing a large voltage and frequency variation with simple, inexpensive controls and a relatively small engine as contrasted to allowing only small variations in voltage and frequency with complex and more expensive controls and a relatively large engine.

The control systems for the generator with signal-conditioning system (Figure 3-6b) is similar to that just described but with some significant differences. The power flow is the same except that the generator must supply the losses of the signal conditioner as well as the electrical load.

When the electrical demand is suddenly increased, the excess power required will (as described above) come from the inertia of the rotating parts, and the generator will slow down. As a result, the generator frequency will decrease. However, because there is no direct relationship between generator frequency and the 60 Hz output frequency, the latter need not change. Thus, the engine speed can be allowed to drop appreciably during the time interval between the application of the load and the time when the engine governor has supplied sufficient excess fuel to increase engine power. As a result, the engine governing requirements are much less stringent. However, as the engine slows down, the voltage produced by the generator will also decrease unless the field excitation is increased accordingly. Thus, the generator and the signal conditioning package must be designed to ensure compatibility.

With both of the arrangements of Figure 3-6, the complexity and cost will depend to a large degree on the requirements placed on the quality of the electrical output, that is, voltage, frequency, and wave shape. It is very important, therefore, that an overall systems approach be used to ensure that the electrical specifications truly reflect the needs of the apparatus that uses electrical power.

Generator Set Signature

Major noise sources in towed and skid-mounted diesel generator sets include the engine, exhaust, intake, cooling fan and generator. A survey of Detroit Diesel generator sets (30 to 750 kW) indicates the engine noise is about 2/3 of the total generator set noise. The cooling fan is the second largest source, averaging 20 percent of total generator set noise. Although not included in this survey, engine exhaust noise can also be a substantial source throughout the frequency spectrum.

Figure 3-7 is a graph of noise in excess of the typical nondetectability limit for the major components of a 150 kW Detroit Diesel generator set. The engine is the largest source, particularly at frequencies of 800 to 3,000 Hz. This data suggests diesel engine noise is broad band, requiring extensive suppression to comply with nondetectability limits. Excessive cooling fan noise occurs at blade

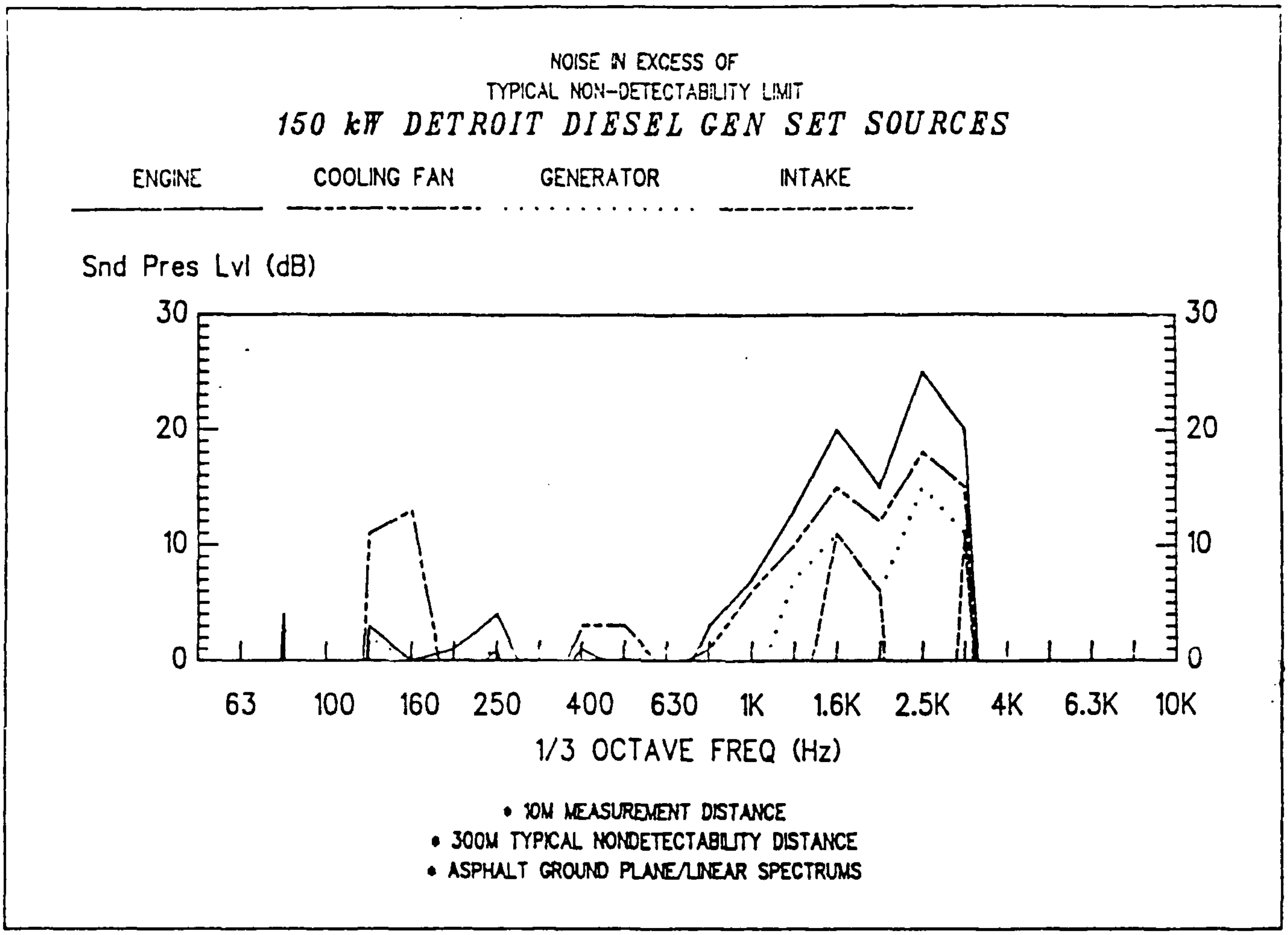


FIGURE 3-7 Sources of noise for 150 kW Detroit Diesel generator set.

passage frequency (130 Hz) and at high frequencies (1 to 3 kHz). High frequency fan noise may be due to turbulent air flow near the fan blades. The generator and intake system are small noise sources, exceeding the nondetectability limit primarily from 1 to 3 kHz.

Gasoline engine generators tend to be quieter than equivalent output diesel powered units. Combustion forces exciting the structure of a gasoline engine are characterized by a lower peak firing pressure and rate of pressure rise than a diesel engine. Reciprocating masses can be kept lower, and piston clearances are generally tighter than in a diesel engine. This yields lower piston impact forces, and transmission of smaller combustion forces to the engine structure. Since gasoline engines have lower excitation forces, large bore and short stroke gasoline engines can operate at high speeds with noise levels less than diesel engines of comparable bore, stroke, and rated speed (Figure 3-8; Priede, 1975).

Figure 3-9 shows noise in excess of the typical nondetectability limit for the 150 kW Patriot Gas Turbine. This data suggests that substantial suppression (10 to 25 dB) for gas turbine noise is necessary if a gas turbine power generator is to comply with the typical nondetectability limit.

Several skid-mounted rotary engine generators are under development for the DoD. Stratified-charge, rotary engine generator sets are regarded as quieter than diesels due to lower mechanical forces, that is, lack of piston slap. Using an acoustical enclosure, rotary engine generator sets can meet current community noise standards (Bolte, 1988). However, compliance with nondetectability limits will likely require additional effort, particularly in engine, exhaust, and cooling fan noise reduction.

SYSTEMS PERSPECTIVE

To make the most effective use of MEP resources, the relationship between the MEP generator set and the supplied electrical loads must be critically explored. Past practices that have tended to freeze the generator-load interface requirements deserve careful reexamination in light of evolving Army 21 demands on future MEP systems. For example, the generator set performance requirements contained in MIL-STD-1332 (see Chapter 2 discussion of power quality) have some unwelcome side effects that discourage design attention to generator-load system interactions.

As mobility and signature requirements increase for future MEP generator sets, systems-level design issues take on greater importance. These systems issues influence the design of the generator sets as well as their role in the larger electrical systems that use them. Their net effect on MEP equipment weight, mobility, signature, and life-cycle cost can be significant. These key interactions are discussed in the following paragraphs, including design tradeoffs required to satisfy conflicting Army 21 performance requirements.

Generator Set Configurations

Key characteristics of MEP generator set components were summarized in the preceding section. Recognizing these characteristics and the need to

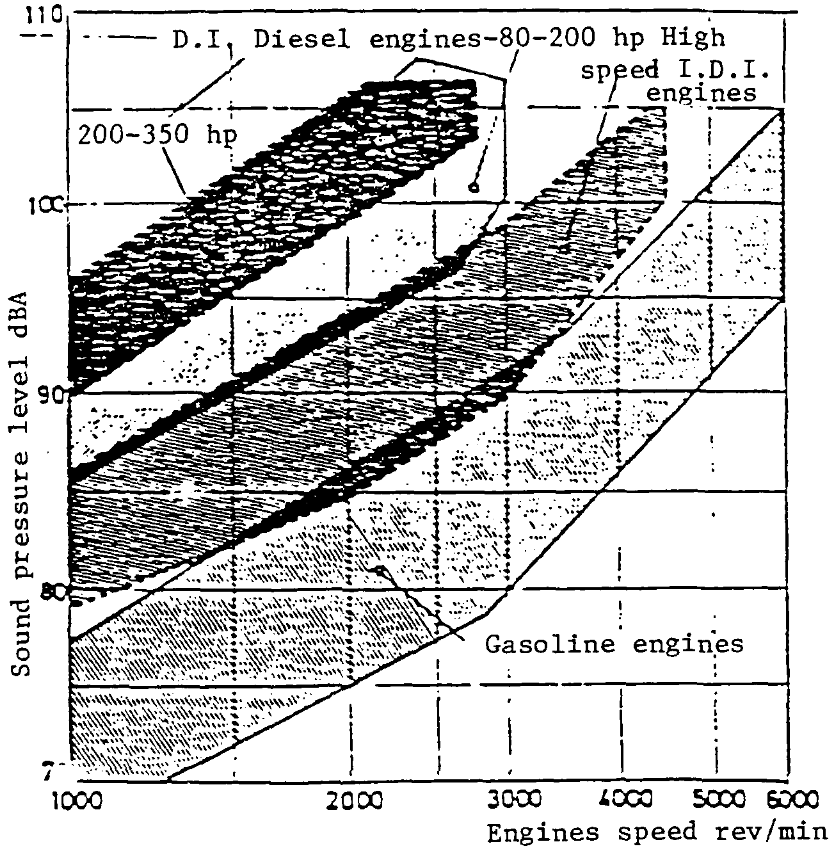


FIGURE 3-8 Comparison of noise levels from diesel and gasoline engines. (D.I. is direct injection; I.D.I. is indirect injection)

SOURCE: Priede (1975).

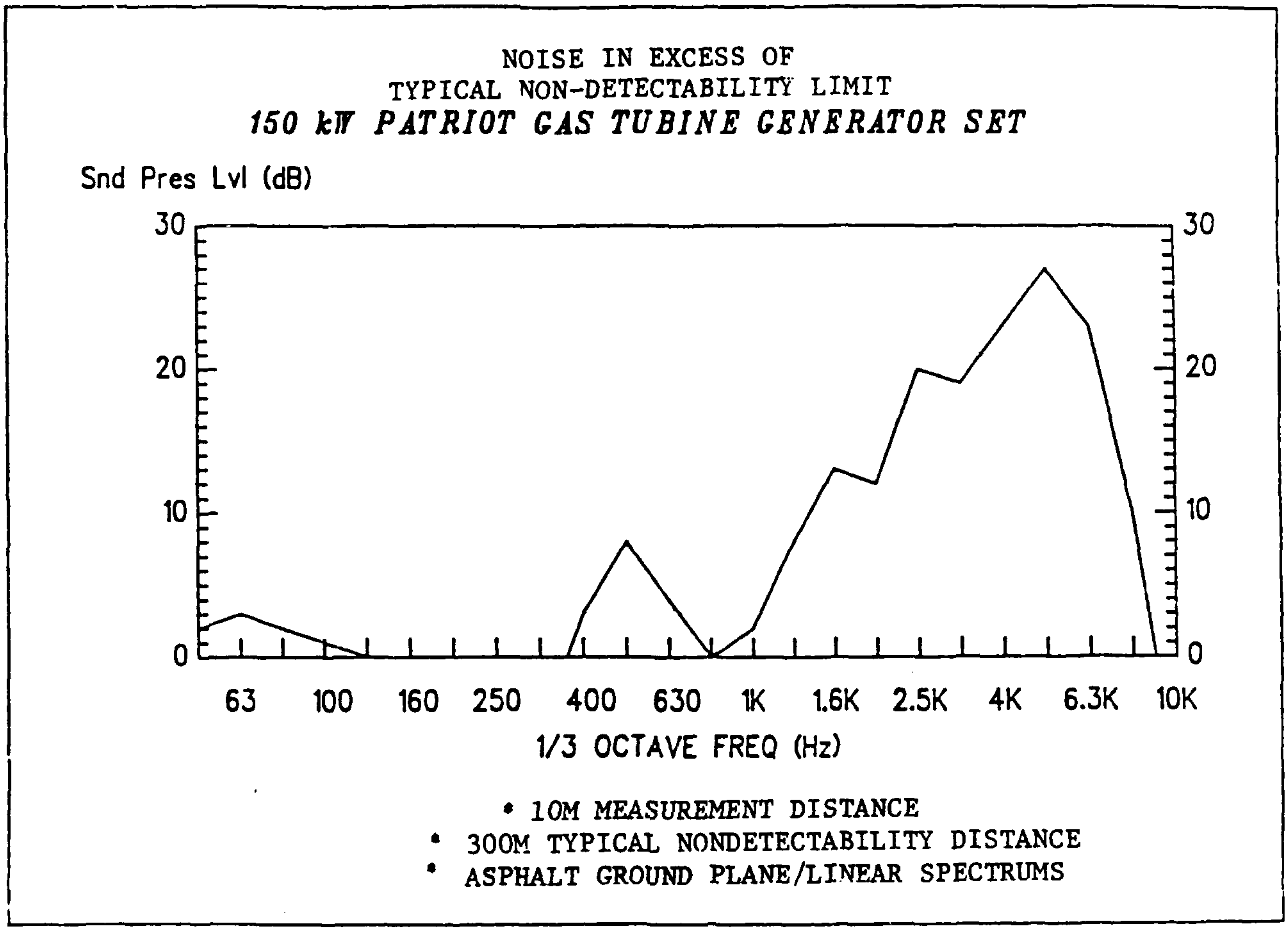


FIGURE 3-9 Noise in excess of typical nondetectability limits for 150 kW Patriot gas turbine generator set.

deliver regulated 60 Hz power at the generator set output, these components can be combined in different ways to comprise the generator.

Three of these basic MEP generator set configurations are shown in Figure 3-10. Figure 3-10a, consisting of a simple combination of engine and alternator, represents virtually all of the existing Army MEP generator set inventory. Since the alternator must directly produce the 60 Hz power required at the output terminals, the shaft speed must be held constant at a fixed submultiple of 3,600 rpm. That is, the maximum engine shaft speed will be 3,600 rpm in this basic configuration, requiring a two-pole generator. (Note that a four-pole generator will demand a shaft speed of 1,800 rpm to produce 60 Hz power.) An engine speed regulator is required to hold the shaft speed constant as the electrical load changes.

The second configuration in Figure 3-10b includes a mechanical speed changer such as a gearbox between the engine and the generator. This alternative makes it possible to use an engine designed to rotate at a speed higher than 3,600 rpm combined with a speed reducer. However, any weight saved by the higher-speed engine is likely to be offset by the additional weight of the speed changer. The alternator must still be sized for 3,600 rpm (or lower) operation. Assuming a fixed speed ratio provided by this changer, the engine speed must be regulated constant in order to deliver fixed-frequency 60 Hz power. In many aircraft systems, the speed changer is designed to have a variable and adjustable ratio to compensate for engine speed variations, using a hydraulic "constant-speed drive" (CSD).

Some of the same results can be achieved electronically by replacing the gearbox with a solid-state power conditioner at the output of the engine-alternator combination (Figure 3-10c). Since the power conditioner is now responsible for producing the 60 Hz output power, the speed of the engine-alternator combination no longer has to be limited to 3,600 rpm or less. Alternator size can thus be significantly reduced both by increasing the shaft speed and by increasing the pole number, as described in the preceding section of this chapter. Engine size can also be reduced by taking advantage of higher shaft speeds. As an additional benefit, the engine speed no longer requires tight regulation since the output 60 Hz waveforms are synthesized electronically. This type of system is used in aircraft "variable-speed, constant-frequency" (VSCF) generator systems.

The attractiveness of this third configuration depends on whether the weight and volume savings for the engine-alternator combination exceed the added power conditioner contributions. Unlike the engine and alternator, the weight and volume of the power conditioner will not drop significantly as the shaft speed increases. Although no firm design data is available, it is unlikely that there will be a compelling weight or volume savings with this configuration compared to the basic 3,600 rpm engine-alternator combination for engine speeds of 6,000 rpm or less, using contemporary power electronics. The shaft speed threshold above which the introduction of a power conditioner provides a net weight or volume savings is very sensitive to future improvements in the electronics power density. These power electronics technology trends are discussed in Chapter 4.

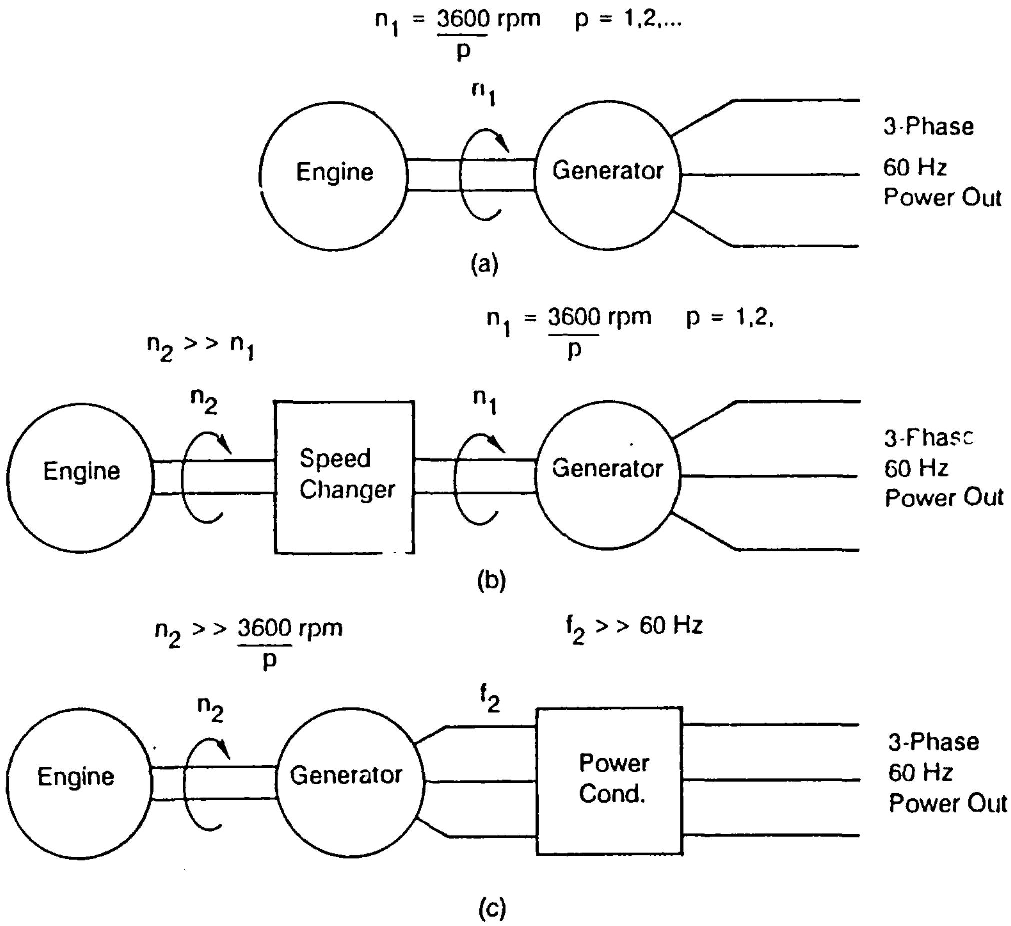


FIGURE 3-10 Basic mobile electric power set configuration (f is alternator output frequency in Hz; n is rotor speed in rpm; p is number of alternator pole-pairs).

Power Quality

As described in Chapter 2, the prevailing MEP system philosophy places a heavy burden on the generator set for maintaining high electrical power quality. The demanding specifications of MIL-STD-1332 result in significant penalties in both engine and generator weight or volume characteristics. Army MEP generator machine lamination diameters and stack lengths must typically be increased compared to their industrial or commercial counterparts to satisfy waveform quality requirements. Engines must typically be oversized to handle transient loading requirements.

While electronic equipment does generally demand high power quality, there are major classes of loads such as lighting and environmental control that are relatively insensitive to power quality. Ironically, these loads capable of operating on "dirty" power often dominate the electrical loading in major system applications such as shelters, accounting for as much as 75 percent of the total electrical load (SAIC, 1988). Such observations raise questions of whether the generator set penalties associated with MIL-STD-1332 power quality standards might be eased by reconsidering the electrical system design philosophy. Recent studies conducted for the Army (Higgins et al., 1987) indicate that electrical equipment designers invariably specify MIL-STD-1332 power quality requirements, regardless of the exact nature of the associated loads. Unfortunately, the heightened mobility requirements for future MEP generator sets is making it increasingly difficult to automatically demand such comfortable margins of security in power quality at the price of weight and volume.

An alternative electrical design philosophy moves the burden for ensuring satisfactory power quality downstream from the generator set to the loads. This approach would likely make it possible to ease power quality requirements on the generator set, reducing both weight and volume. Those "utility" loads such as lighting and heaters, which are relatively insensitive to power quality, would not require any changes to adjust to the relaxed power quality requirements.

On the other hand, those more critical loads that do demand high power quality would require increased power conditioning in their input power stages to compensate for the drop in distributed power quality. In the case of electronic loads, such equipment almost invariably requires ac-to-dc power rectification and stepdown of the dc voltage level to supply the electronic components. Design modifications to enhance this preexisting power conditioning in electronic loads may represent an attractive tradeoff for reducing overall system weight and volume.

A systems approach would also be valuable for addressing the special problems associated with motor starting from generator sets. Induction motor starting can pose serious problems in conventional systems by drawing inrush currents several times their rated values during starting transients that may last several seconds. Both the engine and generator must be oversized to handle this transient motor starting duty without excessive voltage dips. Compact, reliable solid-state motor starters to dramatically reduce these inrush currents provide one alternative approach for easing the starting transient burdens on generator sets. Alternative approaches such as increased tolerance of the other connected loads to

transient voltage dips also deserve consideration as means for reducing overall system size and weight.

Networking

The are many circumstances when it is useful to connect multiple MEP units together to supply the same load (or combination of loads). Such conditions might occur when the total connected load power requirements exceed the capability of a single MEP unit. Generator set paralleling is also valuable for purposes of backup reliability in the case of critical load networks. Finally, short duration paralleling is widely important for providing uninterrupted power during load transfer between a generator set that is being brought on-line and a second generator set that is being shut down.

Existing MEP generator sets have been designed with only rudimentary provisions for paralleled operation. One of the keys to achieving paralleled operation is the initial synchronization of the AC output waveforms for two generators, since failure to properly synchronize can seriously damage both units during paralleling attempts. Army generator sets rated at 15 kW and above can be manually paralleled by operators trained to perform this synchronization. Smaller generator sets have no paralleling requirements at all. Once synchronized, the operators must make sure that the generator sets properly share the load between them at the risk of generator set damage for improper sharing. Such risks have sharply limited Army usage of generator set networks.

A systems perspective strongly suggests that increased use of generator set networks could significantly improve the overall reliability of Army electrical power systems through higher redundancy. Ideally, it would be possible to interconnect almost any combination of available Army generator sets into a reliable network, despite significant differences in generator set type and power rating. Under this scenario, it would be conveniently possible to interconnect a vehicle-engine-driven (VED) generator set with a skid-mounted unit to supply a network of loads.

Electronic generator set controls are already commercially available, which greatly simplify the tasks of synchronization and load sharing. Synchronization can be fully automatic with such controls, and load sharing can be enforced through "master-slave" configurations involving communications between the interconnected generator sets. As the use of electronic engine controls spreads in newly-procured Army generator sets, the incremental cost for these enhanced paralleling capabilities decreases. Establishment of expanded paralleling requirements for new generator sets together with a standardized interest communication interface would significantly expand the networking capabilities of future MEP equipment.

Role of Vehicle-Engine-Driven Generators

As described in Chapter 2, the presently planned role for VED generator sets in Army MEP inventories is surprisingly low in light of the ready

availability of vehicle engines as power sources in the field. From a systems perspective, opportunities for expanded applications of VED generator sets deserve careful examination for achieving rapid deployment of reliable electrical power. The use of VED generator sets, however, may reduce fuel efficiency somewhat and have an impact on the availability of the vehicle. It will have minimal impact on vehicle reliability and durability.

Army 21 mobility demands make it increasingly attractive to integrate power generation capabilities into the vehicle on a broad scale. For rapid deployment situations, VED generator sets provide an attractive means for moving significant amounts of electrical power generation out into the field integrally with the vehicles. Although VED generators are unlikely to match the low-signature characteristics of a well-designed MEP generator set, their capabilities as highly-mobile first-wave power sources are unsurpassed. If necessary, trailer or skid-mounted generator sets can then follow to relieve the vehicles where stationary power generation is required.

VED generators can be used to supplement or replace auxiliary power units (APUs) mounted elsewhere in the vehicle. Power conditioners make it possible to generate regulated power from VED generator sets for on-board electrical loads while the vehicle is moving. Substantial amounts of power can be delivered if the alternator is directly coupled to the engine shaft using a power take-off (PTO) or in-line drive configuration in place of the conventional belt.

In addition to their role as primary sources, VED generator sets can play a valuable role as backup sources for improving power system reliability through networking capabilities described above. The role of VED generator sets in future Army MEP inventories is discussed in more detail in Chapter 5.

CONCLUSIONS AND RECOMMENDATIONS

This chapter has briefly reviewed the technical characteristics of each of the major components of a mobile electric power generating system and how these components interact with each other. By addressing the present state of the art for each of these components and subsystems, an attempt has been made to provide the reader with insights into the nature of both the existing limitations and future opportunities for Army MEP equipment.

Conclusions

- Acoustic signature requirements are likely to become more stringent for future Army MEP generator sets through the specification of nondetectability limits on individual bands of acoustical spectral frequency components.
- Liquid distillate fuels derived from petroleum and various syncrudes will continue to power Army MEP generator sets into the early decades of the twenty-first century.

o Decreasing quality of petroleum crude oil worldwide will require a gradual broadening of fuel specifications in future years, in turn requiring engines that can accommodate this wider range of fuel characteristics.

o Present alternators for Army MEP sets are conservatively designed to deliver high-quality 60 Hz power directly at their output terminals, limiting their maximum rotational speeds to 3,600 rpm.

o The volume and weight of the engine-alternator combination can be reduced by increasing the shaft speed above 3,600 rpm, at the penalty of introducing an electronic power conditioner to deliver the desired 60 Hz output power.

o Present military power quality standards (MIL-STD-1332) have the undesirable effect of penalizing Army MEP generator set weights and volumes. System power density improvements are possible by adjusting the standards to demand greater power quality tolerance by the connected loads.

o Networking capabilities for Army MEP generator sets, which are presently quite limited, provide means for increasing both the flexibility and power availability of fielded MEP units.

o Vehicle-engine-driven generator sets provide an attractive means to increase mobility, reduce deployment times, and provide greater MEP source redundancy when systematically integrated with other classes of MEP units.

Recommendations

o The Army should recognize the substantial advantages of reduced power quality and carefully study its present power quality requirements keeping in mind power conditioning possibilities in both production and use of electricity and, recognizing the system performance implications, establish new power quality requirements for high-performance MEP systems.

o For all power sizes, the Army should evaluate the costs and benefits of integration of the prime mover and alternator in view of the performance requirements of the high-performance MEP systems.

4

FUTURE COMPONENT TECHNOLOGIES

This chapter addresses future developments in technologies for mobile electric power (MEP). It considers different prime movers, direct energy conversion devices, electrical technologies, and signature reduction approaches.

ENGINES AND POWER SOURCES

Intermittent-Combustion Engines Capable of Burning JP-8 as a Fuel

Intermittent-combustion engines capable of using JP-8 as a fuel vary considerably in their commercial availability as well as maximum speed (in rpm), power density, efficiency and part-load fuel consumption (see Chapter 3, section on Engine and Direct Converters). It should be noted that tests at the U.S. Tank Automotive Command indicate power losses of about five percent if JP-8 is used in heavy-duty diesel engines. Engine fuel flow can be adjusted to compensate for this loss. Commercial availability is the greatest for the diesel engine. Table 4-1 shows the size distribution of commercially available diesel engines in the United States, Japan, and Western Europe while Figure 4-1 shows the number of manufacturers.

Other stratified-charge engines approach commercial availability to varying degrees. While the U.S. Army sponsored the early development of the Texaco Controlled Combustion System (TCCS), the most recent experience is from United Parcel Service (Mitchell and Alperstein, 1973), whose fleet of 350 TCCS engines uses a commercially available engine block retrofitted with a special head. Lewis (1986) reported a consistent 30 to 35 percent increase in fuel economy when using diesel fuel as compared with th unmodified gasoline engine version to the same engine with both vehicles experiencing the same service. Lewis states: "It will operate on all fuels in the range between gasoline and diesel fuel, irrespective of octane and cetane ratings". It is known that the TCCS engine has problems with exhaust emissions; this partially explains its lack of commercial use.

TABLE 4-1 Number of Diesel Engine Manufacturers by Power Output and Region

Engine Power, Kilowatts	≤ 3.0	3.1-4.3	4.4-6.1	6.2-8.7	8.8-12.4	12.5-17	18-24	25-34	35-49	50-69	70-99	100-140	141-200
Region													
United States[a]	0	1	1	0	1	1	1	2	6	7	8	7	6
Japan	1	3	3	3	5	5	6	7	8	9	9	10	8
Western Europe	4	9	11	16	17	21	23	27	33	35	32	32	29
Total	5	12	14	19	22	26	29	36	47	51	49	49	43

[a] The U.S. company, Onan Corporation, has an old design of a diesel engine covering the size range from about three to 18 kilowatts (3, 6, 12, and 17.5 kW).

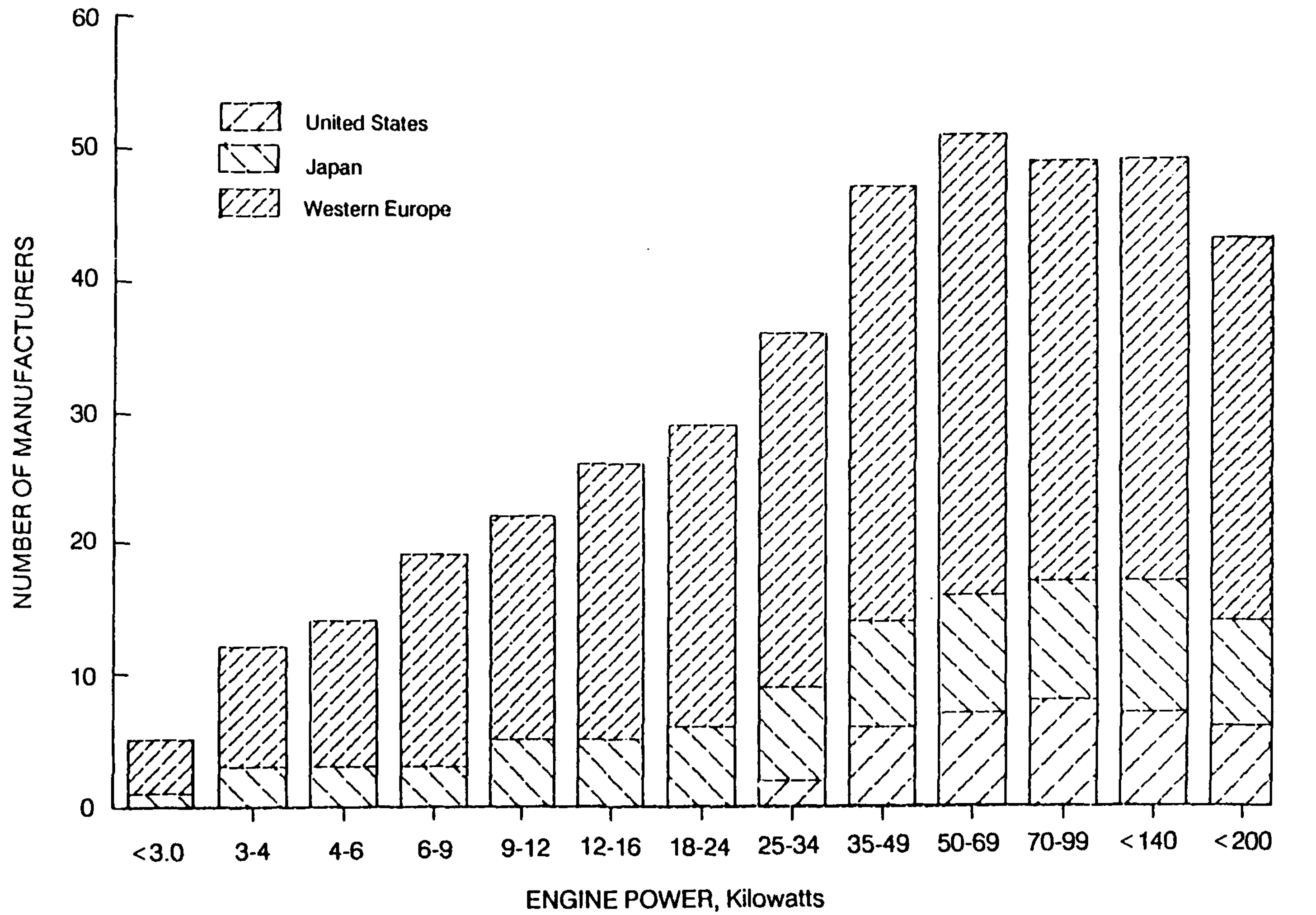


FIGURE 4-1 Number of diesel engine manufacturers. The one U.S. manufacturer, Onan Corporation, that offers an old engine design for some sizes between three and 18 kilowatts is not included.

Deere and Co. have committed themselves to at least partial commercialization of a stratified-charge rotary engine capable of burning diesel fuel. Because of its geometrical configuration, the stratified-charge rotary engine is able to achieve power to weight ratios estimated to be at least 1.3 times those of a homogeneous-charge engine and 1.5 times that of a diesel engine (Mount et al., 1987).

Homogeneous-charge engines can burn diesel fuel with some modifications, that is, use of a low compression ratio or modified combustion chamber because of the lower octane number plus heating of the intake (or fuel) because of the lower volatility of diesel (or JP-8) fuel. Heating of the intake air, as well as decreases in compression ratio, will cause some power loss. In the early days of the internal combustion engine, kerosene (which is similar to JP-8) was commonly used in low-compression-ratio (from 4:1 to 6:1) engines. Today, in undeveloped countries, adapted versions of commercially-available, homogeneous-charge engines are running using diesel fuel (Briggs and Stratton, 1988). Recently, Sonex (Raia, 1987) has developed a combustion chamber that reportedly uses diesel fuel in an approximately homogeneous-charge engine with only a small decrease in compression ratio (about 7:1).

A discussion of future technologies for these engines that can use JP-8 fuel is divided into two different categories, those generally commercially available (the diesel) and those not generally commercially available (the remainder).

Intermittent-Combustion Engines Generally Available on a Commercial Basis

As indicated above, the diesel engine is the only intermittent-combustion engine available commercially and capable of burning JP-8. Because diesel engine technology is very mature, it is unlikely that any major development will occur during the next decade or two that will radically change the basic character of the engine. The improvements are expected to continue to be evolutionary rather than revolutionary.

Most current commercial development in diesel engines is directed toward one or more of the following:

1) Reduced emissions, particularly particulates,
2) Improved fuel economy,
3) Greater power output in a given size engine,
4) Longer life between overhauls,
5) Lower cost per unit output, and
6) Reduced noise level.

Refinements in combustion, fuel injection, and structure are the major factors in most of these areas.

Turbocharging has become a well-established technology used both for greater output from a given size engine and for reduced emissions. Nearly all larger engines are now available in turbocharged versions. In the smaller sizes, however, the advantage is not as great and the small size turbochargers are less efficient. Turbocharging is not used in engines less than 50 kW because of the unavailability and lower efficiency of

small turbochargers. This limit will undoubtedly be pushed down in the future, but whether it is or not is of relatively little practical value in the small sizes.

Along with straight turbocharging, interest remains in developing various forms of turbocompound engines. In these engines, a portion of the output shaft power is developed directly by a turbine. The turbocompound engine has the potential for greater power output from a given size package but at the expense of greater cost and complexity. It is doubtful that they will be of interest in sizes of 200 kW and smaller.

Much has been written about the use of ceramic parts in engines both for longer life and for reduced heat loss. Low heat rejection ("adiabatic") engine designs will not, in the committee's opinion, have a significant impact on the design of engines for MEP uses (NRC, 1987). Some ceramic parts will without doubt be incorporated into diesel engines but, at least in the short term, will not significantly alter the nature of their application to generator sets of the sizes of interest in this study.

Electronic controls are under active development for diesel as well as all other engines. The immediate goal is to produce an engine that is capable of being optimally adjusted to varying conditions. For example, a truck requires a given power at any given combination of load, road speed, grade, and ambient conditions. Adjustments to engine and transmission can cause the power plant to operate in the most effective way to satisfy these conditions. For generator sets, electronic governors have been available for a number of years and are used where close speed regulation is required. It would appear that further use of electronics will modify and improve diesel engine performance but will not alter it in any major way. In fact, the need for engine controls per se is minimal for small generator sets and electronics will more likely be used to control the electrical portion of the unit.

Engine development has been evolutionary for many years and continues so today. Changes come very slowly in this industry! At the present time, there is no technology that appears poised to challenge conventional diesel technology in the next decade or two, perhaps longer. Improvements are being made rapidly but primarily consist of a multitude of small changes rather than major ones.

<u>Application to Electrical Generation</u> Many diesel engines of all sizes have been applied as the prime mover in commercial generator sets. This results in systems that produce good, reliable power but will not meet all of the stringent requirements of the military. In particular, attention needs to be directed toward reduction of noise, infrared (IR) signature, and weight, as well as improvement of cold starting ability.

Because of the economies of scale in small engine manufacturing coupled with the relatively low volume of military generator sets, it is doubtful that much (if any) progress in these areas will be commercially developed to the degree required by the military.

Thus, it appears that two choices are available for the specific development of military generator sets:

(1) Develop special engines for military generator sets, or

(2) Modify standard commercial engine-generator packages to military requirements.

Of these two options, the second appears to be the better choice. It is likely that in each size a commercial diesel engine-generator set can be obtained that will satisfy the basic requirement of producing good quality electrical power. These commercial sets will be in a convenient compact arrangement with reasonable weight, moderate noise level, and good starting ability down to $0^{o}C$ ($32^{o}F$) or below. On the other hand, it is unlikely that any available commercial diesel engine-generator set will satisfy the more stringent requirements for some military applications.

Noise: Although considerable development has been directed toward noise reduction, the requirements for the commercial market are far less demanding than those of the military. It would appear that the most practical method of reducing engine noise to a very low level is through a combination of enclosure to reduce structurally caused noise, and active attenuation of the exhaust. The materials and techniques for both of these types of noise reduction are commercially available but must be specially designed for each type of unit and individual requirement of noise level.

Infra-red signature: Where this requirement is important, there seems no alternative to using an enclosure or other covering. An internal combustion engine by its very nature develops power because it operates with very hot gas. The high temperature internal gas in turn inherently produces hot external surfaces, particularly in and around the exhaust manifold. These hot surfaces can be shielded only by the application of insulation material, either internal or external. At the present time, external treatment by means of a covering blanket or enclosure appears to be the preferred method. Any enclosure can, of course, be a combined treatment for both noise and IR signature.

Weight: Small commercial generator sets have been designed with weight as a significant factor. Diesel engines themselves (recently designed versions) probably cannot be reduced in weight to any significant degree except as the technology gradually develops further. If for no other reason, properly used structural material is required for noise control and reducing weight will, in general, increase noise.

Insofar as the overall weight of the diesel engine-generator set is concerned, decreased weight can best be accomplished by the use of a multi-pole generator with signal conditioning. (The subject of generators is covered in detail in a later section.) With a multi-pole generator the basic electrical current is generated at a high frequency, then converted to the desired controlled frequency. Not only is the generator itself lighter than a conventional generator but the engine can in some cases be reduced in weight by running at a higher speed.

Cold starting: A diesel engine in good condition will ordinarily start readily when both the engine and the ambient temperatures are above freezing. As the temperature drops below freezing, however, diesel engines become more difficult to start. (Once started at any temperature, the diesel engine will run very reliably). The cold starting limit depends on the individual engine model but, in general, a diesel engine in

an environment below about -6.7°C (20°F) can be started only by using some sort of aid. In addition, as an engine wears, its starting ability becomes impaired.

The most commonly used diesel starting aid is the "glow plug" which is frequently, for example, applied to indirect injection automotive engines. In use, the glow plug is energized for a period of time of approximately 20 to 60 seconds and pre-heats the air and the internal engine structure in the immediate vicinity of the plug. The hot glow plug also heats the first few charges of injected fuel. The glow plug, however, is most effective in those engines having a "pre-chamber" design and requires an auxiliary source of electric power for its operation.

Another commonly used starting aid is ether sprayed into the intake manifold of a cranking engine. The high flammability of ether is very effective in aiding combustion during the first few cycles of engine operation. For the same reason, however, it is hazardous and if used to excess can cause serious damage to the engine. The most successful applications are those where a specially designed ether injection system is incorporated into the engine itself.

Intake manifold heaters operate by producing a small flame inside of the intake manifold. Fuel is sprayed directly into the intake manifold and is ignited by a spark. Combustion of this extra fuel heats the incoming air and is effective for cold starting.

With an enclosure around the engine, it should be possible to incorporate a heater into the system to raise the temperature of both the engine itself and the incoming air. Such a heating system should be considered as an integral part of any enclosure design.

Conclusions The diesel engine is well suited as a power source for generating electrical power over the range from 1 to 2 kW on the lower end to the maximum desired for mobile electric power (MEP) generation.

Above about 35 kW, there are many different engines available, both domestic and foreign. As the power level drops below 25 kW, there are essentially no domestic manufacturers (Onan Corporation offers an old design) and relatively few foreign manufacturers. Nonetheless, good, modern, well-designed engines are available over the entire power range of interest. The diesel engine is reliable and rugged. It will require treatment for noise, IR signature, and cold starting ability to meet all of the military requirements.

Intermittent-Combustion Engines Not Generally Available on a Commercial Basis

Although it is concluded above that the diesel engine is well suited as a power source for generating electrical power, the charge to the committee was to look at technologies out to the year 2015. Hence, in the following, other engines under development are considered.

Stratified-Charge, Spark-Ignited Engines

TCCS engine In many ways the TCCS is ideal for MEP units. When used in an Army 1/4 ton, 4x4 utility truck, a minimum of 25 percent improvement in fuel economy was reported with unaided starts down to -32°C (-25°F). The TCCS unit essentially matched the torque and horsepower of the original engine in dynamometer testing. Exhaust noise, while not tested, should be comparable to diesel engines while engine radiated noise should be less because of lower rates of pressure rise in the cylinder. Weight should be slightly less than that of the diesel and rotating speed limitations should be similar. The TCCS is adaptable to a family of engines.

There are problems with the TCCS concept. The first is the lack of commercial interest in spite of a long development history. This means that there will be few, if any, industry-sponsored future developments. This lack of commercial interest is probably due to high exhaust emissions and somewhat higher first cost. From an MEP standpoint these disadvantages may be more than offset by its advantages. However, it is probably prohibitively expensive for the Ft. Belvoir MEP program to bear all future development costs. A second problem, especially for the smaller MEP units, is the anticipated difficulty of physically getting the required injector, spark plug and combustion chamber in a small bore. Another problem is that while its speed limit is probably above 3,600 rpm, it may not be high enough to justify power conditioning.

Rotary Engine The rotary engine has advantages. Its output shaft speed is higher than the comparable reciprocating engine: this is an advantage from the standpoint of generator size as well as engine power density. Its rates of rise for cylinder pressure are typically smaller than for diesel engines meaning lower engine structure radiated noise. Its exhaust noise is usually higher because its ports open more rapidly than do diesel valves. Current military and National Aeronautics and Space Administration (NASA) contracts ensure continuation of development for the larger sizes. There is also development underway for small size units (2 to 3 kW and higher) at Teledyne Continental Motors (Mobile, AL). These engines are designed without injectors and will probably have starting problems with JP-8 fuel.

Deere and Co. have advertised a military family of generator sets. Their one- and two-rotor family cover the power range from 10 kW at 1,800 rpm to 100 kW at 5,800 rpm. They point out the advantage of a major reduction in parts because of their modular (family) approach. The 1,800 rpm basically represents a derating to achieve the lower load power. This raises the same question as that for the TCCS: can the required injectors and spark plug be physically incorporated into the space available in a few kilowatt single rotor MEP? The fuel economy of the rotary engine is less than that of the diesel engine, in part because of its higher surface-to-volume ratio and consequent higher heat transfer, and in part because of its higher leakage. These factors would increase in significance as engine size decreases. In addition, an output shaft rotational speed of 7,200 rpm is probably achievable so that power conditioning may have size and weight advantages at these speeds (see

Chapter 3). This would offer the possibility of load control by speed variation, which would have significant part-load fuel economy advantages. It appears that future development will be in improved sealing, durability, and combustion control.

Homogeneous-Charge Spark-Ignited Engines

Low-Compression-Ratio Gasoline-based Engines As mentioned in Chapter 3, homogeneous-charge engines can operate at high speeds but have problems in burning JP-8 and have high part-load fuel consumption. One approach to accommodate the low octane number of JP-8 would be to reduce the compression ratio to the range of five. The low volatility of the fuel makes starting difficult but some commercial solutions have been proposed. Since starting aids would be required in any event for starts at -54°C (-65°F) they could be used for starting at higher temperatures; the problem is really at what temperature are starting aids needed. Unless additional heat is supplied to the fuel (or manifold), or other provisions made, the lower volatility of JP-8 could cause dilution of lubricating oil and high wear due to unvaporized fuel. Such engines are now in use in undeveloped countries (Briggs and Stratton Model Series 80300, 82300, 132400, 233400, Kerosene Fuel Systems). These engines have both a gasoline and a kerosene tank with gasoline used during starting and warmup. While not a true production unit they are assembled from production parts with some changes in carburetion possibly required. Such an engine should be capable of operation at speeds approaching 7,200 rpm. Since power conditioning would then be required, load control could, under some circumstances, be by control of speed rather than by throttling, with consequent gains in fuel economy. Since complete commercial development of this type of engine is unlikely, some development support would be needed for MEP use: development costs should be minimal.

Sonex Approach Sonex Corporation (Raia, 1987) has under development an engine having a combustion chamber that is claimed to be relatively insensitive to fuel octane number because of combustion chamber design, some in-cylinder charge stratification, and their method of introducing air and fuel-air mixture. Demonstration has been made of a single-cylinder, four-stroke, Honda 3,600 rpm generator set operating on diesel, JP-4, and gasoline as a fuel at a compression ratio of 7:1 (normal value for the gasoline version is 8:1). Heat is supplied to the fuel to assist vaporization (fuel temperature of 93°C [200°F]). Unaided cold starts down to -14.4°C (6°F) were demonstrated but there was evidence of unburned fuel in the exhaust until the engine was warmed up. Knock was not observed on any of the fuels. Peak power was less for all fuels when using the Sonex chamber compared to the unmodified engine. Fuel economy was better for all of the fuels using the Sonex chamber due in part, at least, to leaner operation. While the highest reported speed is 3,600 rpm, there is no reason to believe the approach is more speed limited than any other homogeneous-charge engine. Thus, it would appear that, again, under some circumstances, use of power conditioning would permit load control by speed variation with consequent gains in part-load fuel economy.

Steady-Flow Combustion Engines (SCE) Capable of Burning JP-8

Gas Turbine Engine

Unlike intermittent-combustion engines, the SCE operates as a steady-flow machine (Figure 4-2). In the simple cycle, air is compressed, fuel is burned in the combustor, and the combusted gases expand through the turbine to produce power. The excess power over that required to drive the compressor is available as shaft power. For the simple cycle the ideal efficiency is a function of the pressure ratio across the compressor (or turbine). In practice, because of inefficiencies in the compressor and turbine, thermal efficiency is a function of both pressure ratio and inlet temperature to the turbine.

Because gas turbine flow passages decrease with turbine size and the ratio of circumference to area increases as flow passages become smaller, the efficiency of gas turbines is very size sensitive. The efficiency, and particularly the part-load efficiency, of the gas turbine can be increased by the use of regeneration, that is, using some of the energy in the exhaust to preheat the air before it enters the combustion chamber.

Current gas turbines typically operate at 1040 to 1095°C (1900 to 2000°F) for metal engines and temperatures of 1370°C (2500°F) are predicted for engines using ceramic or specially cooled blades. Simple cycle gas turbines have very high power per unit mass and volume (PMV) but, especially in the smaller sizes, very high fuel consumption. Regeneration aids fuel consumption but is detrimental to PMV and cost. With some changes in nozzles the gas turbine will run on a wide variety of fuels.

The Army has in operation gas turbine MEP units that provide power for the Patriot Missile System. They are 150 kW regenerative units with a pressure ratio of 4:1, two shafts, and an inlet temperature of 1024°C (1875°F). A 37 kW, single-shaft, simple-cycle turbine is also under development with emphasis on light weight, relatively low cost, high reliability and maintainability. Fuel consumption is not as crucial for the intended auxiliary power unit (APU) applications.

As with other MEP units, noise signature for the gas turbine comes from non-engine features such as a gear box as well as from the power unit. Gas turbine power units generally produce higher frequency sound, which is more easily attenuated. Because of the relatively high gas flows and large expanses of metal at relatively high temperature, IR signature can be a problem. However, since an enclosure would likely be required to meet minimum detectability requirements this may not truly be a problem.

In summary, for larger sizes (approximately above 300 kW) fuel consumption is more nearly competitive to that of the diesel and the PMV advantage begins to offset the cost disadvantage. This higher PMV confers a transport advantage with regard to the gas turbine. Below approximately 300 kW, cost (in part because of low volume production) and fuel consumption make the gas turbine increasingly less competitive (See Appendix D for details for projected gas turbine fuel efficiency).

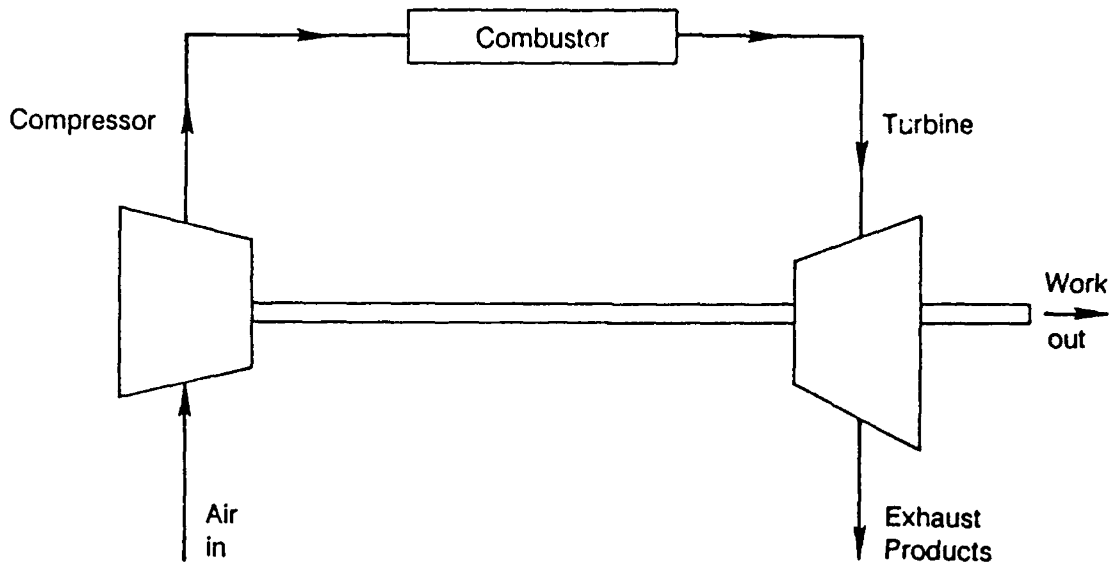


FIGURE 4-2 Schematic diagram of a gas turbine.

Stirling Engines

The Stirling engine, invented in 1816, has a long development history. In the modern version it uses hydrogen or helium as the working fluid in a closed cycle. Generally, a power and a displacer piston are required with a variety of mechanisms, including a free piston, invented to provide the required motions. At different times several large corporations such as Philips, General Motors and Ford have undertaken, and then abandoned, development of the Stirling engine although Philips commercially markets a cryogenic refrigerator that is essentially a reversed Stirling engine.

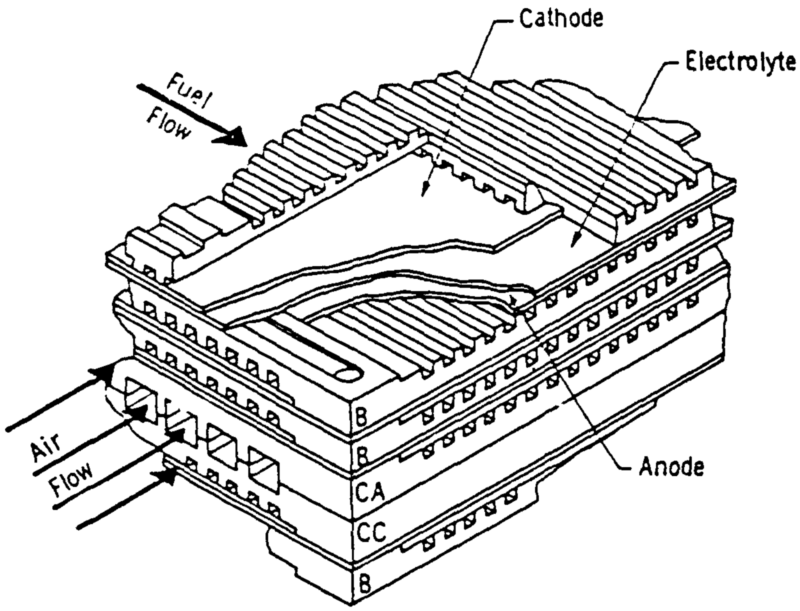
The Stirling engine appears to have a number of attractive features for MEP applications. Combustion is steady flow and noise signature should be a minimal problem. It is relatively fuel insensitive. It may have IR signature problems since a portion of the engine is at high temperature. Its efficiency is directly related to the temperature of the hot part of the engine; new materials could lead to improved efficiency. However, in spite of large expenditures and a long history of development, the Stirling engine is still in the laboratory stage. It does not appear that developments outside the Army will lead to successful units. Furthermore, development costs will exceed all of the resources available to the MEP program. If an enclosure is required (the committee judges that it will be) the signature advantages are minimal. Thus, the committee judges that the Stirling engine is not a viable competitor for MEP (See Appendix E for more details).

Direct Energy Conversion

Fuel Cells

A fuel cell is an electrochemical converter in which its two electrodes consume an externally supplied fuel and oxidant (see Appendix F for more details). Each cell consists of two electrodes with an immobilized electrolyte layer (acid or alkaline, molten carbonate, or solid oxide) between them. These cells can be arranged in stacks (Figure 4-3). Fuel cells are classified by the electrolyte used and operating temperatures differ depending on the type of fuel cell. They are high efficiency converters, typically transforming hydrogen to direct current power with 45 to 60 percent efficiency. Great improvements have occurred in the state of the art but cost and commercial viability are difficult to project.

Hydrogen is by far the most effective fuel for use in fuel cells of all types and sizes between several watts to multimegawatt units. Its catalyzed oxidation rates are very high, even at low temperatures whereas fuels such as methanol, ammonia, and other organic fuels show low activity at low temperature. It's possible that, by the year 2015, a breakthrough in electrocatalysis allowing the direct use of conventional fuels may occur but, based on past experience, this is highly unlikely. Failing such a breakthrough, projections of fuel cell technology should be confined to those operating on hydrogen, methanol, or ammonia. Commercial developments are also occurring with natural gas used as a fuel, requiring a much higher reforming temperature than for methanol.



B - Bipolar plate with process air & fuel channels

CA - Anode DIGAS cooling plate

CC - Cathode DIGAS cooling plate

FIGURE 4-3 Elements of a Phosphoric Acid fuel cell stack (Energy Research Corporation Air-Cooled DiGas[R] System).

For the purposes of the Army, fuel cells have a number of unique advantages: low infrared signature for the low-temperature systems, low noise signature, and few moving parts. In fact, the Army had an extensive methanol-based fuel cell development program until recently. However, with the requirement of a single fuel on the battlefield (JP-8), fuel cells would require the use of a heavy, complex fuel processor to convert JP-8 to hydrogen. This makes fuel cells, even if commercial development is realized, impractical for general use by the Army for its MEP needs.

Fuel cells, however, may have a limited role in the man-portable backpack (hundreds of watts) where batteries have insufficient energy storage. Atmospheric pressure fuel cells, with a fluorinated sulfonic acid polymer electrolyte operating on hydrogen, are capable of 0.7 kW/kg and should be of use in man-portable units if a source of hydrogen is available. Hydrogen in light-weight cylinders or advanced reversible hydrides would weigh about 2 kg/kWh, whereas Kipp-type lithium-hydride water generators would weigh less than 1 kg/kWh. Small units like these are being developed by NASA for extravehicular activity in space but are, at present, expensive.

Batteries

A battery consists of a number of galvanic cells. A primary cell converts chemical energy directly into electric energy whereas a secondary, or rechargeable, cell can allow electric energy to be input, converted to chemical energy, and thus stored (see Appendix G for more details). The Army currently uses small primary and secondary batteries for utility purposes and electronic equipment; larger standard lead-acid batteries are used for starting internal combustion engines and auxiliary power supplies for vehicles. Batteries are also used for such devices as night sights, radar, and thermal viewers. Future uses include laser rangefinders and target designators, mini-bolt lasers, thermal weapon sights, and chemical agent sensors.

Present small batteries include alkaline primary cells, nickel-cadmium and lead-acid secondary cells, and lithium primary cells. It is the intention of the Army that the future system will be standardized around rechargeable lithium batteries in the form of the "universal field battery" proposed for the 1995 time-frame (Gilman, 1987). This battery will be either throwaway or rechargeable. Before the introduction of the universal field battery, the lithium/thionyl chloride ($Li/SOCl_2$) throwaway unit will continue to be used for high-power applications, the present generation of rechargeable lithium cells gradually replacing nickel-cadmium cells. A universal lithium battery can reduce the diversity of battery inventory, can satisfy high current requirements, and have substantial weight and volume advantages compared with magnesium/manganese dioxide (Mg/MnO_2) batteries (see Table 4-2).

R & D programs are in place in the Army to address technical developments of a universal field battery. Battery development is also occurring commercially at Duracell and GTE. Enough chemical variations seem possible to allow the development of a successful universal field battery to meet some of the man-portable needs as part of Army 21.

TABLE 4-2 Typical Energy Densities for Different Batteries and a Supercapacitor

Battery Type	Energy Density (Watt-hr/kg)
Alkaline primary cells	100
Nickel-cadmium secondary cells	30
Lithium primary cells	120 420 for $Li/SOCl_2$
Li/SO_2	2.25 x that of Mg/MnO_2 (2 x volumetric energy density)
Rechargeable Lithium Battery	100
Training battery	110 (> 100 cycles)
Throwaway battery (limited rechargeability)	180 (first cycle) 110 (> 20 cycles)
Universal field battery	220 (100 cycles)
Li_x/CoO_2	> 400
Supercapacitor	2

Supercapacitors may also be a possible technology to provide high pulse power capability. There are also developments occurring at the U.S. Department of Energy on aluminum-air batteries that could provide high energy densities.

The Army's battery R & D policy seems sound but the Army does not currently perceive a need for small portable to semiportable power sources between the class currently producing several watts continuous power, intended to be served by the universal field battery, and small JP-8 field generators of about 3 kW. Depending on the mission requirement, batteries may be able to fill some of this gap, assuming energy densities are sufficiently high. If the energy densities are not enough, fuel cells or a metal-air battery may be able to provide man-portable power for selected missions.

Thermal-to-Electric Energy Conversion

Thermal-to-electric energy conversion produces electrical power from any heat source, given the presence also of a heat sink (or "cold junction"). Three types will be considered: (1) Seebeck effect, using thermocouples, often called thermoelectric energy conversion; (2) thermionic devices, involving the emission of electrons from hot solids into a vacuum; and (3) Nernst effect devices, involving the diffusion under a concentration gradient, of ions through a solid electrolyte. All three types can work from any source of sufficient heat at the right temperature and require a good heat sink. They are all quiet, requiring no moving parts. Their power density is not high. They are not used widely, so repairmen would have to be specifically trained if they were used. At present their cost is high because of low demand. None of these devices are commercially available. They would be difficult to utilize as personal power packs, since they all require a source of considerable heat. However, since all of these are at an intermediate state of development, they could be engineered into designs not presently foreseen.

Thermoelectric Energy Conversion or Seebeck Effect The primary practical use of Seebeck effect devices has been in deep space missions that use heat from nuclear sources (Bennett et al., 1981). However, fossil-fuel heat sources would be very effective and heat sinks using water or air cooling would be much better than the space heat sinks.

Table 4-3 shows some approximate efficiencies of some representative systems (Ioffe, 1957). The second row shows estimates for a future system using p-type semiconductor elements ("legs") now under development (Wood, 1988).

Work on the development of small mobile power sources utilizing thermoelectric energy conversion and fossil fuel sources has been conducted over a number of years (Wood, 1988). However, the recent development of improved silicon-germanium thermoelectric alloys, which can be operated in an air environment, bodes well for the development of significantly superior systems than heretofore (Vandersande et al., 1987).

TABLE 4-3. Efficiencies of a SiGe Thermoelectric Converter Using a Fossil Fuel Heat Source (In Percent)

	High Temp. Burner (1000°C)		Quiet Burner (700°C)	
	Water Cooled Heat Sink (25°C)	Air Cooled Heat Sink (125°C)	Water Cooled Heat Sink (25°C)	Air Cooled Heat Sink (125°C)
Present Semiconductors	12	10	10	8.5
P-Type Leg Developed to Quality of Present N-Type leg	15	12	12	10

The current thrust of materials research is toward the development of materials of much higher conversion efficiencies (Wood, 1988). The basic parameter associated with conversion efficiency is the thermoelectric material's figure of merit. There is considerable room for improvement in figures of merit and, since there is no theoretical limitation on this parameter (Wood, 1984), it is anticipated that much higher conversion efficiencies (~ 15 to 20 percent) may be realized over the next 30 yrs.

There is some interesting work that has been conducted by Teledyne Energy Systems (1987). They have developed a prototype 100 W thermoelectric generator, that uses diesel fuel, and meets all current Army specifications. Approximately 4000 hrs of operating time have been logged on four models. It measures about 16.5 x 16.5 x 10.5 inches and weighs 16.4 kg (36 lbs) without fuel; hence, an energy density of 6.1 W/kg. Fuel for a 12-hour mission would bring the total weight up to about 20.9 kg (46 lb). This unit could certainly be hand carried and is in the man-portable category. Researchers from Teledyne Energy Systems claim that the production of 4000 units would result in a $7,000 unit cost. They estimate that a 500 W unit would weigh about 45 kg (100 lbs).

In summary, the advantages of thermoelectric power are: ruggedness, reliability, versatility, small size, light weight, quiet operation and no fingerprint. The disadvantages are generally low conversion efficiencies and a limited application to small power sources, in the range 100 W to 5 kW.

Thermionic Energy Conversion Power sources based on the conversion of heat to electrical energy by thermionic diodes have many of the desirable attributes of thermoelectric systems. The main distinction is that much higher hot side temperatures are required, the minimum temperature being in the neighborhood of $1400^{o}C$. Thus, the versatility with respect to heat sources is absent and is limited, probably, to nuclear reactors. However, the positive aspect is that thermionic conversion is more suited to the generation of large amounts of electric power--the high-temperature requirement (therefore, high Carnot efficiency) coupled with the high electron emission at high temperatures leads to a high conversion efficiency of the order of 20 percent or greater (Hottsopoulos and Gyftopoulos, 1973).

Current research (SP-100, 1985; DOE, 1986) in nuclear reactor heated thermionic power sources is directed toward the elimination of problems associated with materials in high temperature, high neutron flux environments, for example, degradation of electrical insulators and emitter deformation due to fuel swelling. It is anticipated that these problems will soon be solved and most attention in future (next 30 years) research will be directed towards the development of lower work function materials (for example, by coating the surface with cesium) and the reduction of plasma losses. Consequently, devices operating at much higher conversion efficiencies or much lower operating temperatures should be expected.

In summary, although thermionic energy conversion is not so well tried and tested a system as thermoelectric energy conversion, the basic attributes of reliability (no moving parts), ruggedness, and quiet

operation make this an attractive system for portable high power source applications in the range 50 kW to 1 MW, if the problems of using nuclear heat sources for Army MEP can be solved. This solution seems unlikely in the next 30 years, as is pointed out in the Nuclear Power Source Section of this report.

Nernst Effect Devices A good example of a Nernst effect device is the alkali metal thermoelectric converter (AMTEC). The AMTEC is a device for the direct conversion of heat to electrical energy. The sodium ion conductor beta"-alumina is used to form a high-temperature regenerative concentration cell for elemental sodium. An AMTEC of mature design should have an efficiency of 20 to 40 percent, a power density of 0.5 kW/kg or more, no moving parts, low maintenance requirements, high durability, and efficiency independent of size. It should be usable with high-temperature combustion, nuclear, or solar heat sources. Experiments have demonstrated the feasibility of the AMTEC and confirmed the theoretical analysis of the device. A wide range of applications from aerospace power to utility power plants appears possible (Weber, 1974; Cole, 1983; Bankston, in press; Bankston et al., 1983, 1985; Hunt et al., 1978, 1981).

The operating cycle of the AMTEC is illustrated diagrammatically in Figure 4-4. A closed vessel is divided into high-temperature and pressure and low-temperature and pressure regions by a barrier of beta"-alumina (sodium oxide doped aluminum). The upper region is maintained at a temperature T_2 in the range of 900 to 1300 K. The vapor pressure of sodium at the middle of this temperature range is about 100 kPA (1 atm). The low-pressure region contains mostly sodium vapor and a small amount of condensed liquid sodium. This region is in contact with a heat sink at temperature T_1 in the range of 400 to 800 K. A porous metal electrode covers the low-pressure side of the beta"-alumina barrier. Electrical leads that make contact with the porous electrode and high temperature liquid sodium exit through the wall of the device. Nearly all of the temperature drop across the AMTEC occurs in the low-pressure vapor space. A return line and an electromagnetic pump circulate the sodium working fluid through the AMTEC.

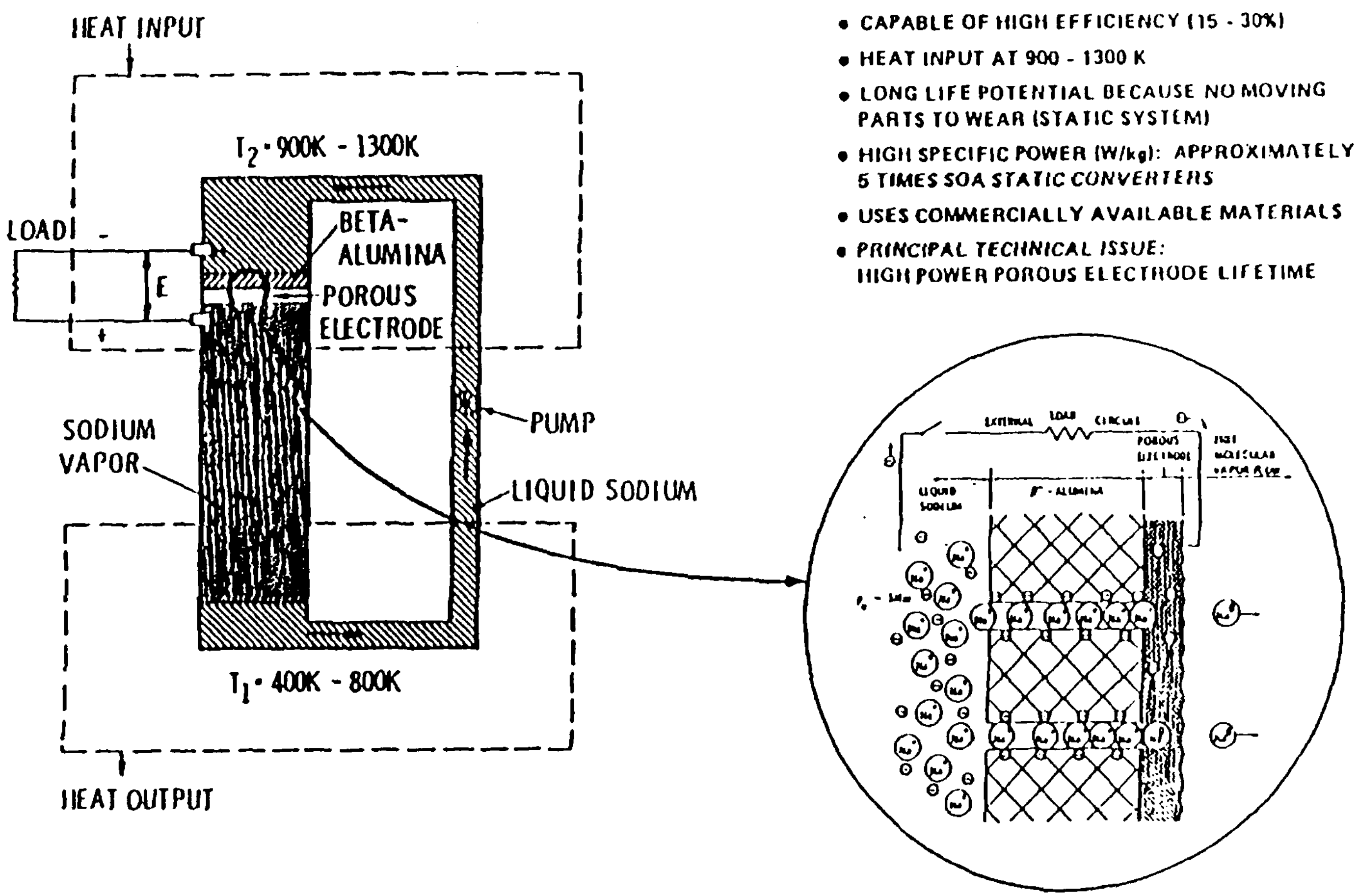
At the beginning of the AMTEC cycle, sodium at T_1 from the condenser enters the hot zone and absorbs thermal energy until it reaches T_2. A pressure differential across the beta"-alumina associated with the difference in sodium vapor pressure at T_2 and T_1 forces Na^+ ions in the solid toward the low-pressure surface. Beta"-alumina is a solid electrolyte that is a permselective barrier conducting only Na^+ ions. Therefore, the reaction

$$Na \longrightarrow \text{electron} + Na^+$$

must occur at the liquid sodium/beta"-alumina interface when current flows. Na^+ ions are driven by the pressure differential toward the low-pressure beta"-alumina surface, causing this surface to acquire a net positive charge. Thus, an electric potential gradient is set up in the beta"-alumina. The electric field across the beta"-alumina builds up until it is strong enough to stop the flow of Na^+ ions.

AMTEC
ALKALI METAL THERMOELECTRIC CONVERTER

CYCLE SCHEMATIC



CHARACTERISTICS

- CAPABLE OF HIGH EFFICIENCY (15 - 30%)
- HEAT INPUT AT 900 - 1300 K
- LONG LIFE POTENTIAL BECAUSE NO MOVING PARTS TO WEAR (STATIC SYSTEM)
- HIGH SPECIFIC POWER (W/kg): APPROXIMATELY 5 TIMES SOA *STATIC CONVERTERS*
- USES COMMERCIALLY AVAILABLE MATERIALS
- *PRINCIPAL TECHNICAL ISSUE:* HIGH POWER POROUS ELECTRODE LIFETIME

FIGURE 4-4 Alkali metal thermoelectric converter.

SOURCE: Cole (1983).

When the external circuit is closed, neutral sodium atoms are formed at the interface of the beta"-alumina and porous electrode by the reverse of the reaction given above. Sodium atoms move by vapor flow and condense on the T_1 surface. The voltage developed across the beta"-alumina barrier forces electrons to flow to the porous electrode surface through the load, producing electrical work. Theoretically, the electrical work output of the AMTEC is the same as the mechanical work that could be extracted by isothermally expanding the sodium vapor from high to low pressure minus internal electrical losses. Sodium ions are in effect "expanded" against an electric field within the beta"-alumina.

The parasitic losses due to radiation and thermal conduction are proportional to the active surface (electrode) area of the AMTEC and the power output is also proportional to the surface area; therefore, the efficiency of the device will be independent of size. Because of this scaling law, the AMTEC lends itself to modular assembly of power generation systems. The size of the system could thus be adapted to the requirements of any particular application or a given power module could be operated at different power levels. Also, because of the exponential relationship between the temperature and vapor pressure of sodium, the efficiency of a practical AMTEC is nearly independent of T_1 up to 600 K and can produce electric power at 15 percent efficiency even when T_1 is as high as 800 K with T_2 = 1200 K.

Since part of the electric power of the AMTEC will be used to run an electromagnetic pump, there are no moving mechanical parts in the device. Also, since the sodium reservoir is externally heated, the AMTEC can be interfaced with a variety of heat sources, including nuclear, solar, or high-temperature combustion. These characteristics make AMTEC well suited for various large and small scale power applications.

The primary technological barrier inhibiting the use of AMTEC as a power source has been the development of a long life, high power, porous electrode. Systems studies have shown that a minimum power density of 0.55 W/cm^2 of electrode area is required for a conversion efficiency of 20 percent or more. Recent laboratory experiments have identified electrode compositions reaching demonstrated power densities of 0.4 W/cm^2 for 1000 hours (Hunt et al., in press) and, in a separate experiment, 0.8 W/cm^2 for 160 hours with no sign of loss (Bankston, in press). Experiments are continuing to repeat these results and to extend the test lifetime. These experiments, however, demonstrate that AMTEC is capable of the predicted high efficiencies and that the primary technological barrier to AMTEC may be finally surmounted. The characteristics of AMTEC make it desirable for remote power applications such as spacecraft power sources, communication relay stations, weather buoys, military equipment, and construction sites.

Nuclear Sources for Mobile Electric Power

Nuclear power, seldom needing new fuel, would seem an ideal source of MEP. However, due to bulky shielding and extremely high cost in some sizes, this proves to be untrue.

Nuclear electric power is generated first as heat, which is then converted into electric power. The heat can be generated by a nuclear reactor using a controlled chain reaction such as is found in an electric utility nuclear power plant or by a radioactive isotope heat source. Usually the smaller heat sources (< 650 W) are the isotopic type and the larger ones are the reactor type. The conversion of heat to electricity can be by Seebeck effect thermoelectric devices using couples of various semiconductors; by differential concentration, solid-electrolyte ("Nernst") cells, which are still under development, not yet in use; and by "external-combustion" heat engines such as Rankine, Brayton, or Stirling cycle engines. The conversion efficiencies run about 4 ± 3 percent for Seebeck devices, 15 to 20 percent for Nernst devices and 20 to 30 percent for heat engines. The Nernst devices, after over 20 years, are not yet developed for manufacture. The heat engines have been used primarily in demonstrations, with a rather small production volume for sale, and their moving parts are subject to wear.

Table 4-4 shows some of the operating and cost parameters of a sampling of nuclear power source demonstrations. As can be seen, the most attractive nuclear power sources that have been tested produce about 1 MW or more of electric power. This is very close to the highest end of the MEP range. The systems are heavy, bulky, and a problem to dismantle safely. They require a different training for operation and maintenance than other MEPs. Their benefit is long operation without fuel additions and a somewhat quiet operation. The moderately efficient ones use reciprocating engines to generate electric power, which keep them from being extremely quiet. In general, the obstacles and costs are high and the benefits are marginal, especially for field use.

The Galileo isotope power source is in the small end of the MEP range, but its cost, weight, and volume (partly due to shielding) are too high for practical use. (The monetary cost alone is totally excessive). So, again, the benefits are marginal and the obstacles are either too high or much too high.

The committee concludes that nuclear electric power has very little chance of becoming a source of MEP in the next thirty years. Other techniques merit R & D funds much more.

Conclusions

Based on the discussion in this and the preceding Chapters, the committee reached the following conclusions:

o No single power source meets all of the MEP requirements; high power density, good fuel economy, a reasonable production base, the ability to use JP-8 as a fuel, acceptable aural and thermal signature, and reasonable first and life cycle costs.

o Diesel engines have the best fuel economy, moderate to low power density, ability to use JP-8 fuel, and are available on a production basis. They also have moderate initial and low life-cycle costs. However, achieving a low signature will require either significant development or considerable added bulk and weight.

TABLE 4-4 Some Previous Nuclear Electric Power Generators, More or Less Mobile

Name	Nuclear Type	Thermal Power	Thermal-to Electric Power Converter	Electric Power	Electric Weight	Built	Comments
Galileo	Isotope	8574 W	SiGe Thermo-electric	650 W	127 lb	1	Replacement cost = $20M each
Snap	Reactor	450 kW	Hg Rankine Cycle Engine	35 kW	1500 lb + Shielding	1	
SM-1 Ft[b] Belvoir, VA	Reactor	10 MW	Steam Rankine	2 MW	2500 tons	1	
PM-3A[a] McMurdo Sound	Reactor	10.4 MW	Steam Rankine	1.5 MW	16 Air Transp. Pkg	1	
Romaskka[c] (USSR)	Reactor	40 kW	Si-Ge Thermo Electric	0.5 KW			

[a] R. L. Loftness (1968)
[b] M. M. El-Wakil (1978)
[c] A. M. Petrosynts (1984)

o Between approximately 10 and 300 kW, commercial diesel engines seem adequate to meet the Army's needs for low-cost, high power density engines. In the range of 1.5 to 40 kW, families of diesel engines (a 1.5, 3, and 6 kW family and a 10, 20, and 40 kW family) appear to be feasible. The family concept should have increments based on commercial engines and generator units. The lower range family must meet all combat zone requirements, is not commercially available, and will require development. For transport reasons, gas turbines would be the most likely engine for MEP units larger than 300 kW.

o With the exception of the rotary engine, stratified-charge engines other than the diesel are not sufficiently developed for production. For the lower power range (less than 10 kW), it is not clear that the required injection and ignition components can be designed for the smaller combustion space of any spark-ignited, stratified-charge engine. The rotary engine can burn JP-8 fuel and would have reasonable fuel economy and acceptable initial (but unknown life-cycle) costs, but, like the diesel, would have signature problems.

o The development of a spark-ignition engine that burns JP-8 fuel in the 1.5-to-10 kW range appears to be one approach for achieving low-signature, high-PMV engines at reasonable cost. This engine could use a low compression ratio (around 5:1) or new technology along with some charge stratification, such as the Sonex system. The low-compression-ratio engine would have poorer fuel economy than a diesel, but should have lower initial costs and less weight.

o Stirling engines have minimal acoustic and thermal signature problems and can burn JP-8 fuel. They achieved low fuel consumption in laboratory demonstrations for kinematic Stirling engines but they are not available commercially or ready for production. They will probably have power densities comparable to that of the diesel with equal or higher first costs and unknown life-cycle costs.

o A non-regenerative gas turbine, when combined with high speed electrical equipment and power conditioning, would have the highest power density of all of the systems; could burn JP-8 fuel; would have the most treatable aural signature although treating the thermal signature would be difficult; is not available, especially in the lower powers, on a production basis and, even if available on a production basis, would have quite high initial and life-cycle costs; and, especially in the smaller power sizes, would have very high fuel consumption.

o For the range of about 1.5 to 40 kW, commercial engines should be used to the maximum extent possible using engine families such as one-, two- and four-cylinder engines. In the range from 40 to 300 kW range, diesel engines appear to be the most likely engines because of cost and performance attributes, although gas turbines could be possible with some technical breakthroughs. Commercial availability should be the main basis for selecting engines in the over 40 kW range. Gas turbines will be the most likely engines in the over 300 kW range of MEP units.

o Batteries or fuel cells using a disposable hydrogen fuel container are the preferred candidates for personal backpacks (in the range of hundreds of watts), with fuel cells suitable only when battery energy storage is inadequate. Fuel cells are not suitable for larger power levels because, among other problems, they cannot effectively use JP-8 fuel.

o Nuclear energy, thermionic, and Nernst effect devices are not considered practical for MEP applications based on their power density, weight, cost and safety.

In summary, no single prime mover offers a clear advantage for all MEPs. The optimum prime mover will differ depending upon the required power output; the specific application; and estimates of the importance of signature, power density and the benefits of power conditioning.

FUTURE ELECTRIC SYSTEM TECHNOLOGIES

Alternators

Development of Army MEP units that utilize advanced electric technologies will require effective systems integration. Alternators can be made significantly smaller and lighter by designing them for shaft speeds above 3,600 rpm, but they will no longer be able to directly produce 60 Hz at their output terminals. As described in Chapter 3, a power conditioner must be introduced in such systems to convert the alternator's high frequency ac output power to 60 Hz. The prime mover, alternator, and power conditioner must be designed together as an integrated system to realize the full advantages of this configuration.

The power conditioner can regulate the voltage amplitude as well as the frequency of the output power, making it possible to eliminate the need for voltage regulation within the alternator. The use of rotor permanent magnets (PMs) in place of conventional rotor field excitation windings and a brushless exciter can provide a significant reduction in alternator weight and volume (Koerner, 1985). Permanent magnet synchronous motors presently find extensive use in machine tool drives, and have been used experimentally in a large aircraft alternator with a power density of 22 kW/kg (Brockhurst and Dougherty, 1981).

The use of powerful rare-earth PM materials such as Samarium-Cobalt (SmCo) has been limited during the past two decades to special applications that warrant the premium cost of these high energy-product materials. The introduction of Neodymium-Iron-Boron (NdFeB) magnets over the past three years is now dramatically changing this situation by offering magnets more powerful than available SmCo magnets at a significantly lower cost (Bohlman, 1987). The prospects for economic applications of NdFeB magnets in future MEP alternators are greatly improved as a result of these continuing developments.

The introduction of a power conditioner also makes it possible to consider entirely different classes of machines in place of the standard synchronous alternator. For example, the self-excited induction alternator can provide a rugged, cost-effective alternative to the synchronous alternator when electronics are available to regulate the output power characteristics. Another alternator candidate is the switched reluctance (SR) machine, which provides an extremely robust rotor structure containing no magnets or windings on the rotor (Sugden, 1987). Although such features make the SR machine appealing for high-speed, high-temperature power generation, the SR machine is incapable of delivering 60 Hz sinusoidal

output power without a power conditioner to shape the output waveforms. Opportunities for the SR or induction alternator are most likely to develop in association with high-speed prime movers such as gas turbines operating at shaft speeds of 10,000 rpm or above.

Significant reductions in the mass and volume of MEP units can be achieved my integrating the alternator more tightly both mechanically and structurally with the engine prime mover. Present engines and alternators used in Army MEP generator sets are designed as independent components mechanically coupled together during final assembly. Alternators can be designed to permit commercial components to share the use of shafts, bearing, housings, and cooling systems with the integrated engine assembly, providing substantial reductions in system weight, volume, and parts count. Large diameter "pancake" alternators are presently being supplied in integrated assemblies with large diesel engines for diesel-electric locomotives. A recently introduced Belgian armored personnel carrier uses a similar integrated engine-alternator assembly as a key component in its electric propulsion system (Surlemont, 1985).

More advanced engine-alternator integration schemes have been proposed that include the electromechanical components as an integral part of the engine itself. Free-piston Stirling engine generator sets are being investigated that eliminate the rotary alternator altogether in favor of linear reciprocating alternators designed into the walls of the engine cylinders (Berchowitz et al., 1987). Although such linear alternators tend to require more copper and iron than their rotary counterparts for a given power rating, the overall impact on system weight and volume may still be distinctly positive due to the highly-integrated design.

Since heat rejection plays a major role in determining alternator dimensions, reductions in weight and volume can be achieved by either improving the cooling system or building the alternator with improved materials that can tolerate higher operating temperatures. Engine-alternator system integration steps might allow the alternator to share a liquid cooling system with the engine, providing significant heat transfer advantages over the air cooling used in all present MEP alternators. New inorganic polymer wire insulation schemes are being introduced that can significantly increase the maximum safe operating temperature for alternator windings to 450^{o}C or higher.

As an alternative to increased operating temperatures, new materials also provide avenues to alternator weight and volume reductions by generating lower losses. Cobalt-bearing ferromagnetic materials such as Permendur can dramatically improve the operating efficiency of high-frequency alternators when used in place of conventional iron alloys, but the price penalty is significant.

A dramatically different approach seeks to reduce weight and losses by eliminating the use of ferromagnetic materials in the alternator design altogether. In the absence of the conventional iron to conduct and concentrate the magnetic field, much larger currents are necessary to produce these fields. These elevated currents would result in prohibitively high resistive losses in the windings or unacceptable copper weight and volume requirements if classic machine design techniques were applied. Superconductivity provides a means for dramatically increasing the current density in the machine windings without incurring these copper loss or weight penalties.

Cryogenic superconductors are presently applied commercially in large medical-imaging magnets as well as in large alternators under development. Unfortunately, the need for cryogenic liquid helium cooling necessarily limits the scope of possible applications for this technology because of the substantial weight, volume, and logistical penalties imposed by the cooling system.

There is presently much international excitement over recent advances in the development of high-temperature superconductors. Despite the impressive advances achieved in raising the critical threshold temperature for superconductivity to approximately 100 K, major new breakthroughs will be needed before such materials become attractive for use in electrical machines (Foner and Orlando, 1988). Superconductivity is unlikely to be attractive for Army MEP alternators as long as cryogenic cooling is required. Nevertheless, the potential for weight and volume reductions provided by room-temperature superconductors, when and if they arrive, are very substantial (DeDoncker and Novotny, 1987). Given the unpredictability of future fundamental breakthroughs, superconductor technology should be carefully monitored to assess its potential for practical application in MEP equipment.

Power Conditioning

The 1980s has witnessed major advances in power electronics component technologies that sharply reduce the size, weight, and parts count of power conditioner subsystems. As a result, it is becoming increasingly attractive to introduce power electronics into high-end Army MEP applications where high power density requirements are particularly demanding.

There have been two major related development paths during recent years that have been driving the major technical advances in power electronics components. The first of these is the accelerated development of new classes of power semiconductors with high input impedance metal-oxide-semiconductor (MOS) gates (Chen, 1987). Recently introduced devices in this class include power MOS field-effect transistors (MOSFETs), insulated-gate bipolar transistors (IGBTs), and MOS-controlled thyristors (MCTs). The vital significance of the high impedance gate is that micropower signals applied to the gate terminals can control very large amounts of power flowing through the main device terminals, making the input-output power gain of these new devices extremely high. Unlike past generations of conventional thyristors, the output current can be turned 'off' as well as 'on' directly from the gate terminals.

In addition, high power gain makes it possible to dramatically reduce the size and complexity of the associated gate-drive control electronics. Power device design improvements have increased device ruggedness during switching, making it possible to shrink or even eliminate the need for bulky protective snubber circuits that are conventionally used to limit device switching stresses.

The second key power electronics development has been the rapid evolution of "smart-power" integrated circuits (ICs) that combine low-voltage digital and analog logic together with high-voltage power

devices up to 1,000 volts, all on the same piece of silicon (Rumennik, 1985). By combining smart-power integrated circuit capabilities with the MOS-gated power switches described above, complete switch gate-drivers that previously required large printed circuit cards filled with parts can now be compressed into a single smart-power intergrated circuit (Mannsmann et al., 1987). Twenty-to-one reductions in parts counts for commercial motor drive converters have already been achieved by applying this new technology, with impressive weight and volume savings as well. Such large parts counts reductions hold significant promise for system reliability improvements.

Several major manufacturers are actively competing to develop smart-power IC technology with expanded capabilities for on-board logic complexity and higher voltage and current ratings. Although the automotive electronics market is providing the principal competitive battleground today, it is clear that the full range of industrial, commercial, and military power electronics applications will benefit from smart-power integrated circuits development. For military applications, the size, weight, and parts-counts advantages provided by smart-power ICs are all vital to high-end MEP applications.

In addition to the new power electronics components described above, aggressive development is underway to develop new power circuit topologies that apply these components to best advantage. In particular, high-frequency resonant converter circuits switching at frequencies from 20 kHz to several megahertz are being perfected to shrink the size of the power converter inductor and capacitor components (Steigerwald, 1984). In addition, new types of capacitors are being developed, such as the high power multilayer ceramic capacitors (Cordingley, 1987), which offer significant improvements in both capacitor size and maximum operating temperature.

By applying these combined technical advances, the power density of aerospace logic power supplies has grown by nearly an order of magnitude to 1.53 W/cm^3 (25 W/in^3) during the past five years, with further increases to 6.1 W/cm^3 (100 W/in^3) expected before 1990 (Figure 4-5). The use of higher switching frequencies in resonant-type converters is likely to have similarly-impressive effects on future motor and generator power converters (Divan, 1986).

Despite the impressive performance improvements delivered by recent advances in power electronics technology, the importance of cost in determining future applications cannot be overstated. Dramatic reductions in parts, and power semiconductor learning curve yield-cost trends, are combining to lower the cost of new power electronics converters in commercial-industrial applications. For example, the cost of variable-speed ac motor drives for low integral-horsepower pump and fan applications has dropped to approximately one-fifth of the 1978 levels, with additional reductions expected (Bartos, 1988). Similar cost reductions must be demonstrated for military-qualified power converters to make it appealing to apply power electronics in future high-end MEP generator systems.

These recent major advances in power electronics technology have sparked considerable new R & D activities in the aerospace industry developing advanced electric-based actuators and accessories in the quest for

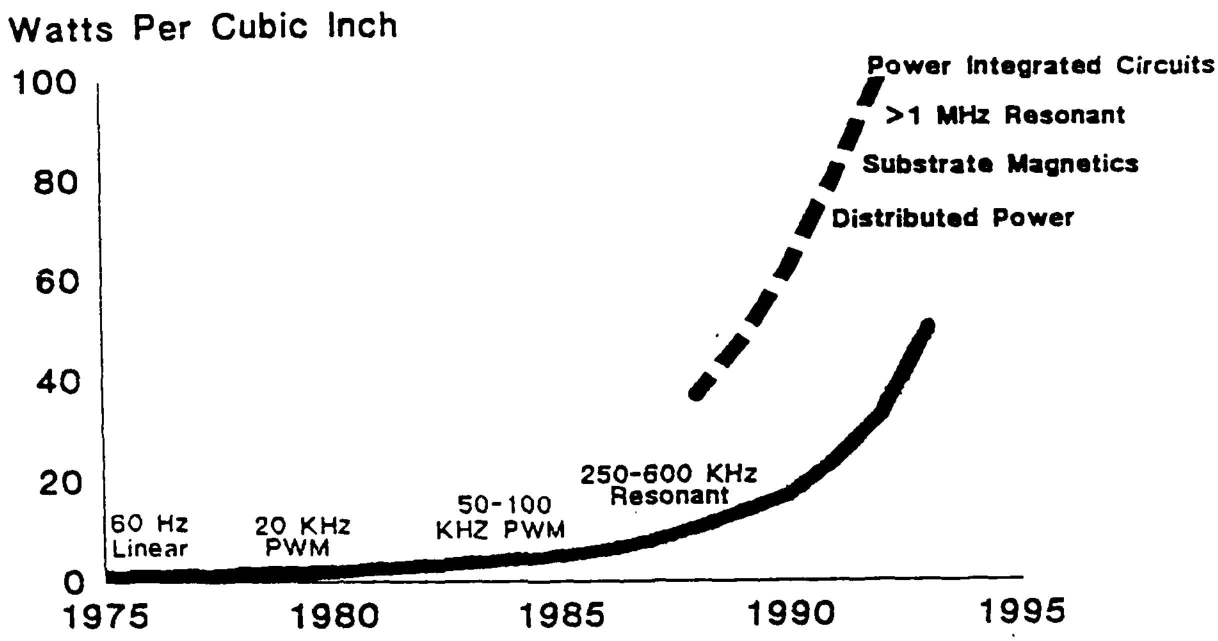


FIGURE 4-5 Impact of new power electronics technology developments on power density trends for military-qualified dc-to-dc Power Supplies

significant aircraft weight reductions and performance improvements. Although the "all-electric" airplane has been discussed for many years, high-power-density power electronics may provide the missing technology to now make "power-by-wire" electrical systems viable competitors against established distributed hydraulics systems (Leonard, 1984). Military and commercial aerospace manufacturers are all actively evaluating the impact of the new technology on future 1990s aircraft designs through laboratory and flight testing. The Air Force is initiating a multiyear program to evaluate and encourage the development of advanced "power-by-wire" technology.

As a result of the high payoff for minimizing weight, aircraft manufacturers have demonstrated their willingness to invest in technologies that can improve the power density of key accessory systems, including electrical power generation. Recent experience with aircraft 400 Hz variable-speed, constant-frequency (VSCF) generating equipment used in the F-18 fighter provides useful insight into the performance advantages of integrated high-speed generators and power electronics converters. The VSCF system converts power from the high-speed jet engine shaft (varying from roughly 15 to 25 thousand rpm) into constant-frequency regulated 400 Hz power using a combined high-speed alternator and power conditioner, as described earlier in Chapter 3 (see Figure 3-10). This 400 Hz power is then distributed throughout the aircraft.

The 40 kVA VSCF unit in the F-18 weighs 80 pounds, yielding a power density of 1.1 kVA/kg for the alternator-converter combination (no prime mover). As a result of the high alternator speed and 400 Hz output frequency, this power density is between 5 and 10 times the comparable power density for a conventional Army MEP 60 Hz alternator machine operating at 3,600 rpm. Accumulated reliability statistics indicate that the average mean-time-between-failure (MTBF) for the F-18 VSCF units in the field is approximately 2000 hours, roughly three times better than comparable hydraulic constant-speed drives. The Air Force is now funding new work to apply recent power electronics technology improvements to double the power density and MTBF figures for new VSCF equipment.

The cost of this specialized VSCF equipment is high compared to that of conventional Army MEP alternators, reflecting the high-end Air Force performance requirements. Nevertheless, technical progress demonstrated in such programs will provide valuable data to the Army in evaluating the role of advanced power electronics in future MEP units as the cost of the power electronics decreases in volume applications.

Widespread Army use of modern power electronics technology is likely to first occur in an application where the special features of a power conditioner are required. Vehicle-engine-driven (VED) generator sets may provide just such an opportunity by making it possible to efficiently deliver regulated dc or 60 Hz power while the vehicle is moving at variable speeds. Strategic decisions regarding the makeup of future Army MEP inventories, including the role of VED electrical power, will have major impacts in determining the nature of these opportunities.

Conclusions

The committee reached the following conclusions regarding future electric systems technologies:

o Alternator size can be reduced significantly by operating at speeds above 6,000 rpm, but power conditioning is then required. At these higher speeds, new electrical power-conditioning technologies can substantially reduce generator size and weight.

o The use of new, economically attractive materials, improved cooling, and integrated design of the alternator with the engine prime mover, can all lead to improved power densities of MEP units.

o The potential for weight and volume reductions of generator sets with the use of room-temperature superconductors, if developed, are substantial. Hence, superconductor technology development should be carefully monitored for application to MEP equipment.

SIGNATURE REDUCTION

Noise Reduction Methods

Current skid and towed power generators as well as potential vehicle platform noise indicates a comprehensive aural suppression program is necessary to meet nondetectability goals. Several components of the power generator may require attenuation including the engine cooling fan exhaust and the intake.

Acoustical enclosures can reduce the noise produced by all the components of a power generator. Enclosures are often used to ensure compliance with community noise criteria. Little has been done to reduce noise by treatment of individual sources such as engine, cooling fan and exhaust. However, compliance with nondetectability limits, as well as volume and weight constraints, suggest that measures, other than enclosures, also need to be developed.

Federal regulation of heavy truck and bus passby noise has created an extensive diesel engine noise reduction technology. Substantial generator engine noise reduction can be achieved by adopting attenuation methods developed for on-highway diesel truck applications.

Noise produced by combustion forces can be reduced by 2 dB(A) by retarding engine fuel injection timing. Tighter piston skirt-to-liner clearances have lowered piston slap forces, decreasing engine noise 3 dB(A) in one case. Structural changes, such as ladder frame elements, eliminate out-of-phase motion of the crankcase walls, reducing both block and oil pan noise. Molded composite acoustical covers, with integral decoupling layers, permit 50 percent or greater reduction of noise produced by cylinder blocks, oil pans and other engine surfaces. Increases in block stiffness have also reduced engine noise compared to earlier models. Extensional (surface) damping materials have been used to reduce noise radiated from external engine surfaces by 30 to 50 percent. Isolation methods have reduced oil pan and rocker cover noise 50 to 90 percent.

Lower engine operating speed can have a dramatic effect on the noise level but obviously reduces power output. In a vehicle study of the General Motors High Mobility Multipurpose Vehicle, a reduction from 3,600 rpm to 1,800 rpm lowered vehicle noise 14.5 dB(A).

Use of automotive cooling fan technology would provide a substantial noise reduction in both towed and vehicle driven applications. Use of unevenly spaced fan blades with rotating ring shrouds, and reduction in shroud and fan tip clearances are common automotive fan noise suppresion techniques. Longer blade chord lengths, reduced fan inlet flow distortion, and swept blade designs are other possible methods to reduce fan noise.

Exhaust system noise should also be examined. As Figures 4-6 and 4-7 reveal, exhaust gas and muffler shell noise is usually broadband. It is caused by structural resonances induced by exhaust gas flow and drivetrain vibration. Double wall exhaust pipe and muffler construction substantially reduces structural noise. Frequency content of exhaust gas noise is usually related to engine firing order and harmonics. Properly designed muffler baffles can significantly reduce exhaust gas noise.

Intake noise is characterized as a low frequency resonance related to engine firing frequency. Substantial insertion loss can be obtained using Helmholtz resonators integrated into the inlet-air cleaner design.

Another approach to controlling noise is through active noise control by which a sound is generated to cancel out the source of noise. This technology is impractical for generator sets over the total frequency spectrum and especially for frequencies greater than 400 Hz. However, the technology is practical for frequencies less than 400 Hz. Active noise suppression could likely be applied to low frequency attenuation in automobile interiors and could also be used in commercial truck interiors. For the next 10 to 15 years, reduction of engine noise without enclosures or active noise control is not practical. Enclosures are transparent to longer wavelengths or lower frequencies sounds. Thus, generator sets with enclosures present a situation suitable for the active attenuation of low frequency sounds of less than 400 Hz. Hence, the committee recommends that the Army explore active noise control techniques for application to generator sets and, at the very least, monitor the important commercial developments that are occurring.

Conclusions and Recommendations

Extensive noise reduction will be required to meet nondetectability limits in either towed or engine driven applications. The dominance of diesel engines as prime power for mobile power generators in the next decade will require particular attention to the engine, exhaust and cooling fan noise sources. Adaptation of on-highway noise technology will permit substantial reduction of diesel generator aural signature. However, use of new techniques, like active noise control, may be needed to assure compliance with nondetectability limits.

Gas turbine generator noise reduction may not be much easier to achieve than the diesel. Excessive high frequency gas turbine noise will require maximum noise treatment. In some cases, gas turbines may be louder than diesel engines at moderate (500 Hz) and higher frequencies. Again, use of

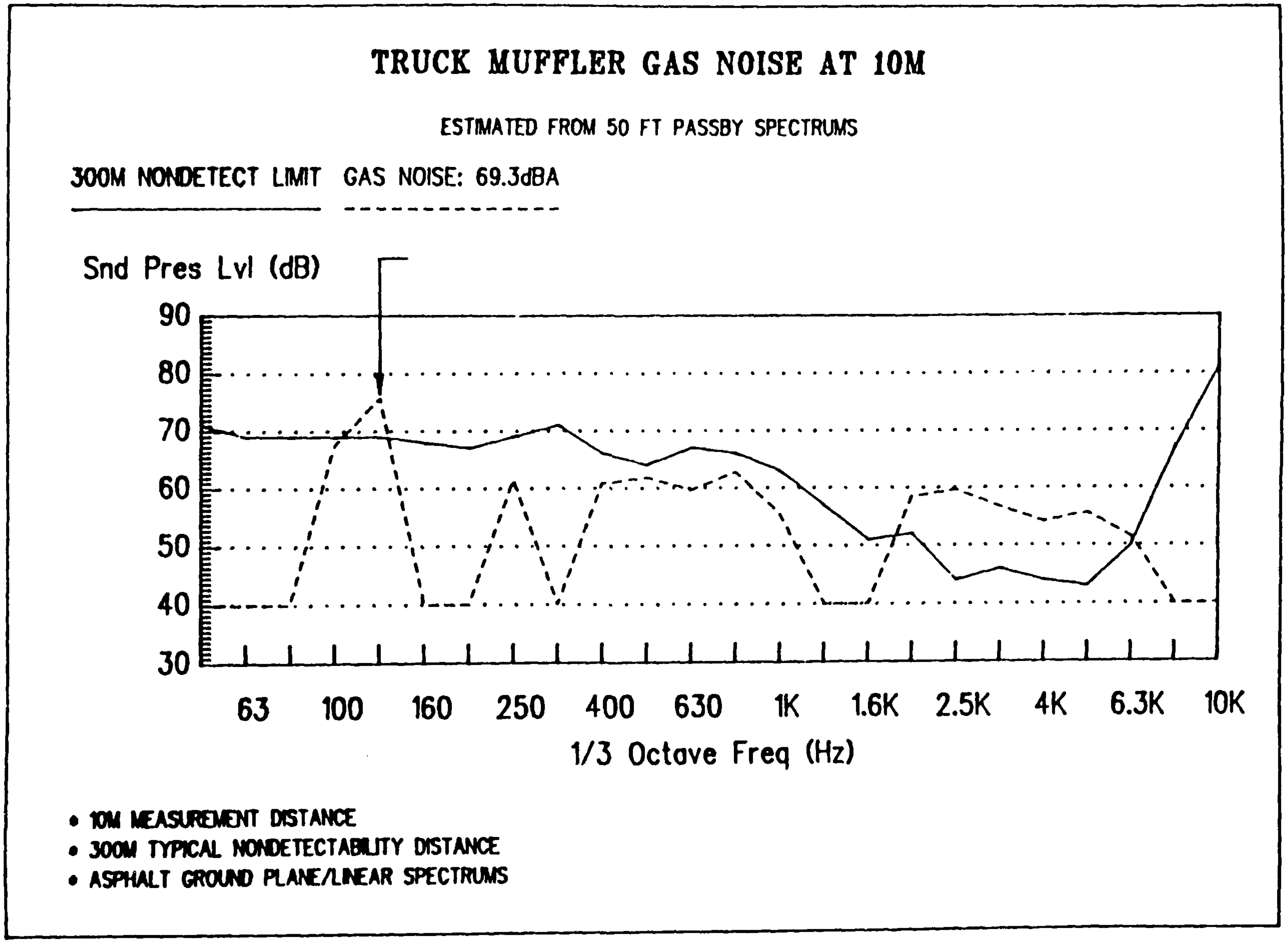


FIGURE 4-6 Truck muffler gas noise at 10 meters.

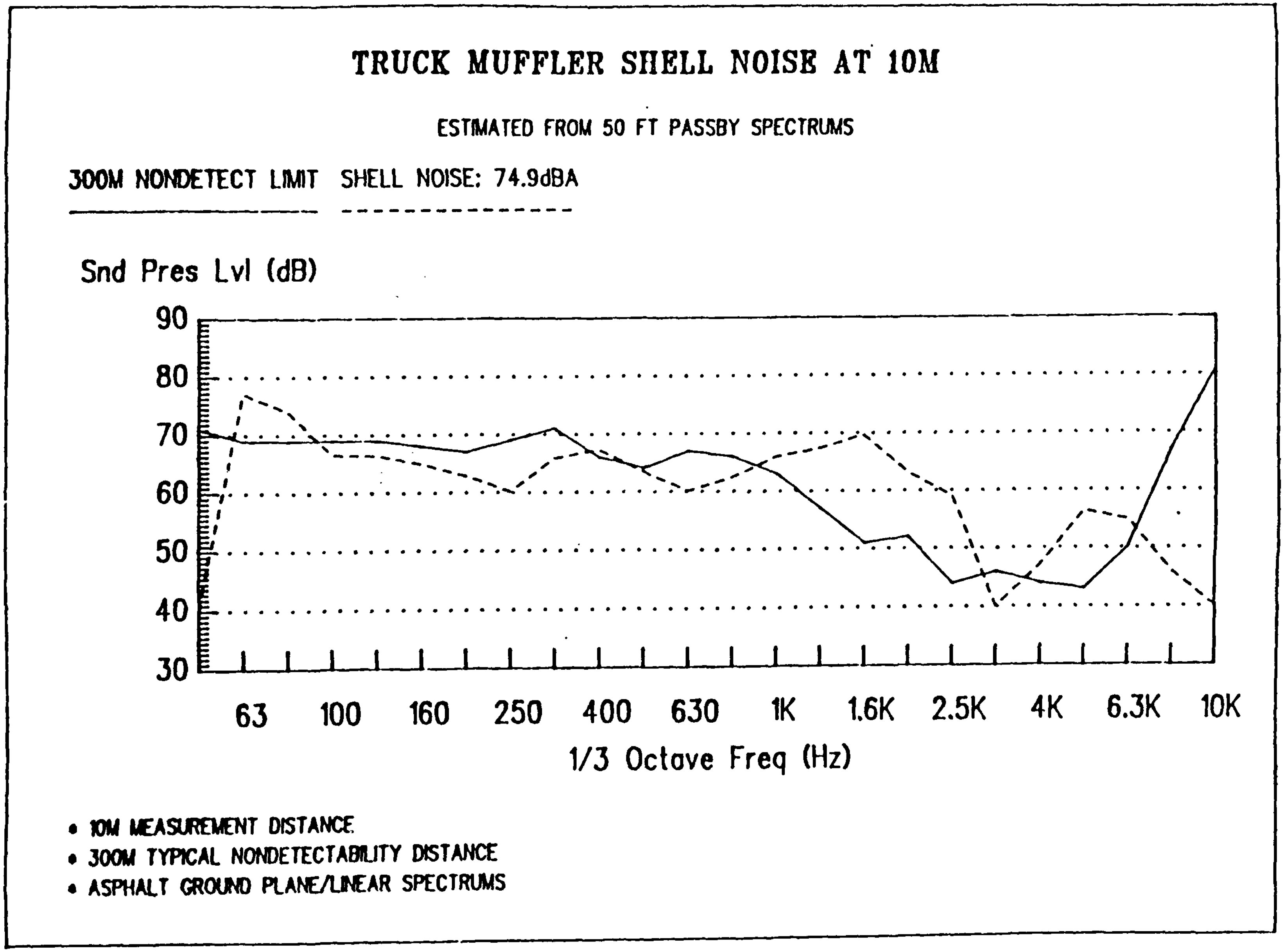


FIGURE 4-7 Truck muffler shell noise at 10 meters.

techniques developed for truck engine noise reduction will be useful. However, active noise control and other experimental methods may be necessary to meet typical nondetectability limits.

Stratified-charge rotary engine generators may be somewhat easier to quiet than either the diesel or gas turbine. However, substantial use of noise reduction technology, in addition to acoustical enclosures, should be applied if rotary diesel generators must comply with a typical nondetectability limit.

There are commercial developments occuring in active noise suppression that the Army should explore and monitor for possible application to generator sets. The committee recommends:

o The Army should explore active noise control techniques for application to generator sets and, at the very least, monitor the commercial developments occurring in this area.

Infrared Reduction

MEP sources used in high-sensitivity applications must have external metal parts subjected to low heat loads (internally-generated warmth, solar heating) shielded, and netting for visible-light camouflage must have IR radiation characteristics similar to those of the ambient background (vegetation, etc). Particular attention must be paid to the exhaust system parts. For diesel engines, with their comparatively low air flow per unit power output, mufflers with the correct resonant frequency are a practical way to suppress sound signature. These must be carefully shielded to avoid IR detectability, and tail-pipes must be angled so that the hot plume does not cause heating of the surrounding background. Visibility of hot parts from the air must be considered. Gas-turbine exhaust parts present a different and more difficult problem, since their air throughput per unit power output is very high and the tail-pipe requires unrestricted flow, which must be exhausted more or less vertically. External shielding, internally cooled by forced air convection, can be used around tail pipes, and careful design and choice of angle of the tail pipe can help make detection from the air difficult. Design considerations may include the use of shrouds around exhaust plumes diluted with ambient air to screen internal hot metal parts as far as possible.

When man-portable power sources are considered, it should be remembered that infantry personnel themselves can easily be detected by forward looking infrared imaging, and the portable power source must not make them more visible. Two-person lift devices are not operated while being carried, and are easily camouflaged by netting. Portable manpack units (Chapter 5) should not show hot parts (for example, hot exhaust systems). Electrochemical converters (batteries and small fuel cells), operate close to ambient and will have no high-temperature parts. They should blend into the IR image of personnel without difficulty.

Electromagnetic Radiation Reduction

The potential for MEP sets to emit electromagnetic (EM) radiation that can be used for directional detection increases significantly when power conditioners are used. Power conditioners operate at frequencies that are much higher than 60 Hz. The only way to suppress these emissions is to package the systems in such a way that the MEP set does not become a radiating antenna. Proper packaging involves the correct dressing of leads, rounding corners of enclosures, sizing enclosures so they are not resonant cavities, design of cooling ports for EM attenuation, and proper shielding. All of the above are well known techniques, but require great attention during the design process so all the potential emissions are trapped and attenuated at the source.

It is particularly important to note that the attenuation process converts the EM energy to heat and sound energy. Thus, the acoustical and infrared problems are aggravated by the process of suppressing the EM signature. A systems approach to the design process is essential.

5

FUTURE MOBILE ELECTRIC POWER SYSTEMS

This chapter addresses the different types of mobile electric power (MEP) plant technologies that can meet the requirements outlined in preceding chapters. It incorporates the technology assessment outlined in Chapter 4 to arrive at conclusions regarding the optimum MEP unit for different Army needs. Referring back to Figure 2-2 in Chapter 2, there are the two basic classes of MEP sets: man-portable and vehicle-portable. The man-portable units are limited to relatively small power ranges because of weight constraints but these power ranges can change with advances in technologies. The vehicle-portable power plants are either vehicle-mounted or vehicle-transporatable, the first permanently attached to the vehicle, the second those that can be removed from the vehicle at the point of use. Previous solutions for meeting MEP needs cannot be depended on to lead to the required MEP units for the Army 21 battlefield.

Under the Army 21 scenario, MEP units intended for use near the front lines or in battle should have high power densities and minimum signature. Unfortunately, a number of factors are reducing the likelihood that MEP units of the future will meet Army 21 requirements. First, Army acquisition policies, to minimize initial costs, depend on commercially available equipment. Second, the basis of issue process, which identifies committed users of new equipment, has a past history of prematurely halting advanced generator development programs. Third, the implementation of nondevelopmental procurement may displace innovative approaches in favor of marginal quick fixes. The existing Generator Acquisition Management Execution (GAME) plan fails to respond to the requirements of Army 21 and, as far as the committee can discern, there is little evidence in the current Army procurement plans that the distinct roles and interrelationships among the different MEP classes are recognized or exploited to advantage.

MAN-PORTABLE SYSTEMS

Personal

One aspect of the Army 21 concept is the possibility that each soldier should carry a power backpack after the year 2000. This has already been

examined in various connections, for example, in the early 1980s as an individual 400 W air-conditioning unit for clothing for protection against chemical and bacteriological agents.

Another type of portable power pack will be more probable after the period from 2000 to 2005. This may provide power for individual communications equipment, detectors, and sensors, for the most rapid response possible. It could also provide satellite communication capability, allowing the use of a continuously-updated liquid-crystal display, active battlefield map. Finally, perhaps with a small hybrid storage package, it could provide power for advanced electrically-powered weapons. All these electronic devices will use DC power. In general, continuous power requirements for electronic equipment are progressively falling, although demands for equipment may increase in the 2000 to 2010 year context. Supply logistics indicate a minimum mission requirement of 12 hours.

Considering batteries for a 12-hour, 150 W (average) mission, 18 kg of primary alkaline cells, 60 kg of nickel-cadmium (Ni-Cd) cells, and 4.5 to 10 kg of lithium (Li) cells (corresponding to the range 420 to 180 Wh/kg, see Chapter 4) would be required. A sulfonic acid polymer (SPE) fuel cell with a Kipp hydrogen generator operating on lithium hydride and water might weigh only about 3 to 4 kg total (fuel weight, including water, about 1.5 to 2 kg). If nickel/titanium (Ni/Ti) pressurized hydride storage of hydrogen is to be used (as for astronaut backpacks), effective fuel reservoir weight would be much greater, about 10 kg. In contrast, storage using advanced hydrides or the use of compressed hydrogen in novel lightweight cylinders might weigh only 3 to 5 kg.

The acoustic noise and infrared (IR) signatures of the electrochemical devices would be close to zero and, unlike internal combustion engine systems, generally have a pulse load capability much higher than their nominal power output. However, among the electrochemical power sources, only the high-energy-density Li cells, the SPE fuel cell, and possibly the aluminum-air battery system deserve consideration.

A potential alternative might be a glow-plug internal-combustion engine of model airplane type, coupled to a high-speed generator. Such a unit could be made quite light, but it would require intensive silencing and a lowered IR signature for practical backpack use. A weight of about 1 kg for the mechanical unit is possible (10,000 rpm glowplug motor, 1 kW/kg, 10,000 rpm alternator, 1 kW/kg). However, acoustic and IR shielding (including the cooling system that must then be introduced) is estimated to weigh up to 5 kg. Although it is not clear that these engines could use JP-8 fuel, the low efficiency (under seven percent) would result in a high fuel requirement (about 1.8 kg for the 12-hour mission). Total weight will therefore be about 8 kg. While this is not unreasonable, vibration, unreliability, and short life would probably make it unacceptable, even if its cost and research and development (R & D) requirements would be small. In addition, a lightweight battery would probably be needed to provide peaking capability, as will be the case for all heat-engine devices sized to provide the average load.

Thermoelectric devices are silent, but require IR shielding. Their low efficiencies require relatively high fuel loads and result in rather heavy devices. However, Teledyne Energy Systems (Timonium, Md.) has produced a prototype 100 W thermoelectric system that uses diesel fuel. It weighs 21 kg including the weight of fuel for a 12-hour mission.

A sodium heat engine might be attractive if passive means to return sodium from the sink to the source (for example, wicks as in a heat pipe) could be found. Such a system may be capable of 20 percent efficiency, requiring only 0.63 kg of JP-8 fuel for the 12-hour basic mission. The system is silent (except for burner noise), but would require IR shielding. A conservative estimate for the system power density, based on that of the sodium-sulfur battery, is 60 W/kg, so that total weight, including fuel and IR shielding, might be 4 kg.

The final heat engine of interest might be the free piston Stirling engine with a linear alternator. A 150 W unit would weigh about 4 kg and require 0.5 kg of JP-8 fuel for the baseline 12-hour mission. The unit will be relatively silent, but will require IR shielding. Total weight will therefore be about 5.5 kg, including fuel. A peaking battery, weighing perhaps 1 kg, will be needed. Table 5-1 summarizes weight and power density of different man-portable systems.

The committee reached the following conclusion and recommendation regarding man-portable MEP units:

Conclusion:

o Currently, there is no satisfactory source of personal power of less than one kilowatt, except for batteries at small power levels. All sizes of MEP sets, except possibly man-portable backpacks, will have to meet the JP-8 fuel requirement. Man-portable MEP backpacks will probably use direct energy conversion devices. Batteries are preferred although fuel cells using disposable hydrogen containers should be considered if battery energy storage capabilities are insufficient.

Recommendation:

o The Army should study its need for personal man-portable MEP units. If power requirements exceed battery capability, the use of fuel cells with disposable hydrogen cartridges are judged by the committee to be the most viable potential candidate although high speed engines and other conversion devices might be possible. Army battery development for personal power should continue at the same level of activity since it is a promising technology for personal power if the power needs are small (approximately less than 150 W).

Two-person Portable

The two-person portable units are MEP sets, depending on how technology develops, in the range from one to several kilowatts (perhaps on the order

TABLE 5-1 Estimates of Weights and Power Densities for a 150 Watt Man-portable Device with 12-hour Capacity

Technology	Weight (kg)	Power Density (W/kg)
Batteries		
Primary alkaline cells	18	8.3
Nickel-cadmium cells	60	2.5
Lithium cells	4.5 to 10	15 to 33
Fuel Cells		
Sulfonic acid polymer		
with hydrogen generator	4	37.5
with hydride storage	10	15
Small engine-generator	8	18.75
Thermoelectric (JP-8 fuel)	21	7.2
Stirling engine-generator	5.5	27.3

of 6 to 7 kW). They are envisioned to be used in a combat situation and light enough that two soldiers can change their position, carrying the unit over some distance. Hence, there is a need for high power density and low signature. In this power range, diesel engines with a family concept (a 1.5, 3, and 6 kW family) appear feasible to meet the Army's requirements. Achieving low signature would require either significant R & D or considerable added bulk and weight.

Other stratified-charge engines are not significantly developed except for the rotary engine. The rotary engine could have power density advantages (both on a weight and volume basis), and run at higher speeds with consequent alternator advantages in size, in comparison to the diesel engine. Rotary engine families could also be developed. The committee judges that it will be difficult to engineer the injection and ignition components into the space of these small engines. However, small rotary engines without injectors are under development by Teledyne Continental Motors.

Instead of stratified-charge engines, another attractive approach is to modify a spark-ignition (SI) engine, such as lowering the compression ratio or redesigning the combustion chamber, so that JP-8 fuel can be burned. Fuel economy would be worse than a diesel but these engines should be cheaper, lighter, and have lower noise signature, as well as be constructed from standard commercial parts.

Gas turbines, in this range of 1 to 6 kW, would have high power density but poorer fuel economy than a diesel engine. They are not available on a commercial production basis and would have high initial and life-cycle costs.

Complicating the issue in this size range is the need of Army 21 for power regarding two-person portable units. However, the higher speed SI engine might incorporate power conditioning to realize advantages in size and weight. To achieve high-performance MEP units, a systems approach to integrating the design of the prime mover and the alternator should be used.

VEHICLE PORTABLE SYSTEMS

The vehicle-portable systems are divided into vehicle-transportable and vehicle-mounted categories (Figure 2-2). The vehicle-transportable are either towed behind a vehicle or can be unloaded whereas the vehicle-mounted are either auxiliary power units (APU) or vehicle-engine-driven (VED) units.

Vehicle Transportable

The vehicle-transportable units can range from the small 1.5 to 10 kW units, which could be individually unloaded by hand or with the use of mechanical aids, such as a winch, at the point of use, to the larger units of many tens or hundreds of kilowatts that are towed on trailers behind vehicles. The size range of 1 to 6 kW has already been discussed. For the larger power ranges of from about 10 or 15 kW to 40 kW, a family

concept could also be developed (a 10, 20, 40 kW family). Again, modified spark-ignited, diesel, rotary, or gas turbine engines could provide power at these levels. Diesel engines are available commercially; a family of rotary engines is under development by Deere and Co. for the range from 15 to 75 kW.

In the range from 40 to 300 kW, diesel engines appear to be the most attractive because of cost and performance attributes, with commercial availability an important consideration. Gas turbines as prime mover could be possible with some technical breakthroughs, providing the advantage of high speed and reduced alternator size. For the large size engines over 300 kW, gas turbines are the most likely candidates.

However, for power levels of 10 or 15 kW and above, the decreased fuel efficiency of the SI engine in comparison to the diesel engine would be a severe drawback. A gas turbine powered MEP set at these levels would have the advantage of high rotative speed; a direct-drive, simple-cycle, gas turbine would have the smallest and lightest total package (prime mover, generator, and controls) by a factor of one and a half to two and a half. Its high frequency noise signature would require minimum treatment to achieve a low aural signature in comparison to the diesel and rotary engine. It would require considerable treatment to achieve a low thermal signature because of its low thermal efficiency and consequently high exhaust temperature. It is not clear that it is advantageous to mechanically "gang together" two smaller units to form a larger unit; the combined unit would probably be larger and less efficient than a new, single-unit design. Its fuel consumption will be almost an order of magnitude higher than a comparable diesel or rotary engine; so will its first cost. Consequently, the committee judges that, from a system standpoint, the gas turbine in this size range is less desirable than the diesel, rotary, or SI engine.

While diesel engines in this size range are available, there is not the multiplicity of manufacturers, particularly in the United States, that exist for the production of the larger size engines. As a matter of interest, during the energy crisis, there was considerable development activity in the United States in this size range of diesel engines; at one time it was projected that 25 percent of the smaller gasoline engines would be replaced by the diesel. The diesel is probably heavier as a prime mover than either the gas turbine, rotary, or SI engine; is probably limited to 3,600 rpm although new injection systems might allow somewhat higher speeds; is the most fuel efficient of the candidates; is probably the most difficult to quiet because of the low frequency component in the exhaust noise; would have the lowest exhaust temperature and, therefore, should require the minimum of thermal suppression; could readily be turned into a family of engines to supply different power ranges; is readily serviced by Army technicians since the Army is already dieselized and the technicians would not require new training; and its initial cost will be relatively low especially if the use of small diesels for other purposes increases as energy prices increase.

The rotary engine, in this size range, can be operated at a speed of 7,200 rpm or higher (the speed is limited by available injection equipment), which would permit a reduction in generator size and weight in comparison to the diesel engine; the prime mover portion of the system

would be lighter than the diesel engine; would have somewhat higher fuel consumption than the diesel; could readily form a family of engines having three to four different sizes using the same basic rotor design; would have initial cost comparable to a diesel; would not have well established reliability at this point in time; would be quieter than the diesel because of the higher fundamental frequency of the exhaust and the somewhat lower structural noise; but would probably have higher development costs because there is less development experience and background in rotary engines.

The committee reached the following conclusions and recommendations:

Conclusions:

o The most attractive MEP units in the range of 1 to approximately 15 kW would use diesel or low-compression (or other modified) SI engines as the prime mover.

o The low compression SI engine is not an attractive technology above the 10 to 20 kW range.

Recommendations:

o *The Army should conduct an engineering study of whether the* low-compression ratio SI engine, or a modified combustion system engine, (either reciprocating or rotary) is more feasible than the diesel engine in the 1 to 15 kW power range. In this range, commercial engines should be used to the maximum extent possible using engine families such as one-, two-, and four-cylinder engines.

o *As long as there are only limited* R & D funds, the Army should closely monitor commercial and military developments for rotary and gas turbine engines in the 30 to 50 kW size range and larger. One of the top priorities for R & D funds should be signature suppression for the current prime mover, the diesel engine.

Vehicle Mounted

The planned Army vehicle inventory is projected to total approximately 332,000 units in 1990, 95 percent of which are in the light- and medium-duty classes. This large number of diesel-powered Army vehicles represents a major potential source of mobile electric power that is currently untapped. As discussed earlier in Chapter 2, vehicle-engine-driven (VED) power can provide unique advantages of rapid electric power deployment integrated with the first wave of fielded vehicles. Even if the vehicle engine does not serve as the primary power source for on-board electrical and electronics equipment, use of VED power as backup or redundant sources can play a crucial role in improving power system reliability with minimum weight and volume penalties.

Present and planned usage of VED power in Army MEP inventories is minimal. The new CAME plan developed for the next round of Army MEP equipment procurement projects that only 800 Army vehicles, or 0.25

percent of the 1990 total inventory, will require provisions for delivering 60 Hz ac "under-the-hood" power. The General Motors light-duty High Mobility Multipurpose Wheeled Vehicle (HMMWV) and Commercial Utility Cargo Vehicle (CUCV) are presently equipped with only 12V dc power as standard equipment, making them incapable of supplying conventional 60 Hz ac loads. After examining the available evidence, the committee has come to the conclusion that VED power is a highly valuable MEP resource that is grossly underutilized in today's Army inventory and future procurement plans.

VED power for use as Army MEP sources can be provided in a variety of configurations depending on application requirements. A major subclass of applications requires the vehicle to be stationary during power production. One of the most straightforward approaches for delivering regulated 60 Hz "stationary" VED power is to add one or more extra ac alternators belt-driven by the engine. This configuration requires a governor to hold the engine speed constant at 1,800 or 3,600 rpm to deliver regulated 60 Hz, 120 V output power. Tests of prototype "under-the-hood" belted power systems have been carried out at the 5 to 6 kW level on a CUCV.

Alternatively, a more aggressive approach is under investigation for integrating larger amounts of VED power directly into the vehicle drivetrain using "pancake" alternators. According to this approach, an alternator large in diameter but short in length is designed to attach to or replace the flywheel of the vehicle's diesel engine. Sufficient space is available between the engine and the transfer case to accommodate the in-line alternator without major changes in the vehicle design or weight. As in the case of the belted alternators, engine speed is held constant while the vehicle is stationary to deliver regulated 60 Hz output power. The Ft. Belvoir Research, Development and Engineering Center is investigating this approach for delivering VED power outputs up to 30 kW in medium-duty trucks.

The engine transfer case power takeoff (PTO) provides another candidate means of extracting engine power for electrical generation. This approach uses the PTO to drive a hydraulic pump which, in turn, drives an electrical generator located remotely in the vehicle. A prototype system consisting of a CUCV with a modified S-250 communications shelter has been developed using this PTO-hydraulic pump configuration to deliver 5 kW to an environmental control unit. Unfortunately, VED energy efficiency suffers due to the introduction of the extra mechanical-to-hydraulic and hydraulic-to-mechanical energy conversions.

For those applications that require VED power generation while the vehicle is "on the go", alternative configurations combining alternators with power conditioning are being explored. Although a variety of specific configurations involving belted, pancake, dc (rectified) and ac alternators have been proposed, the key new element is the addition of a power conditioner to convert the raw input power into regulated 60 Hz output power despite variations in engine speed. The introduction of one or more storage batteries into the design makes it possible for such a system to continue delivering regulated power to the load(s) even when the vehicle slows to very low speeds or stops completely.

The VED power configurations briefly described in the preceding paragraphs are representative of the wide range of alternative means for extracting electrical power from Army vehicle engines. It should be emphasized that VED power is not being proposed as a candidate for replacing more conventional stationary MEP units as the primary source of electrical power in the battlefield. Army vehicle engines have not been designed for minimum acoustic and IR signatures, and it is very unlikely that they will match the signature characteristics of well-designed MEP units in the future. Vehicle signature results for the HMMWV supporting this conclusion are provided in Appendix H.

Nevertheless, despite these signature limitations, VED power provides unique advantages for MEP applications including high mobility, rapid deployment, and cost-effective source redundancy. A major share of these advantages can be captured with only modest modifications of the standard Army vehicle designs to accommodate VED power components. Considered from a systems perspective, Army MEP capabilities can only benefit from the appropriate integration of VED power resources into its future mobile power generation inventories. The committee recommends:

Recommendation:

- The Army should move as rapidly as possible to vehicle-mounted units that provide onboard power generation using the vehicle engine as the power source.

APPENDIX A

STATEMENT OF TASK

The committee will undertake the following tasks:

o Review information about the existing family of mobile electric power plants deployed by the Army (technical specifications, operating statistics, cost of operations, personnel requirements, etc.).

o Review the relevant R & D program activities of the Logistics Support Directorate and PM-MEP.

o Assess the state-of-the-art of mobile electric power generation technologies, including those currently available, technologies likely to become commercial in the next five years, and technologies that may mature in the 1990 to 2015 period.

o Assess the cost effectiveness of potential technologies with highest priority, taking into account probable R & D costs to maturation, and the value of meeting military criteria, which cannot be met with current technology.

o Identify the kinds of fuels that will be available within the time frame.

o Discuss the results of the assessment in a final report. In regard to the most likely candidate technologies, the report will make recommendations on several R & D strategies the Logistics Support Directorate may profitably pursue in order to ensure the development and fielding of cost effective mobile electric power plants that meet Army requirements for the 1990-2015 period. These strategies will consider the costs and benefits of selected mobile electric power technologies in respect to such considerations as ease and economy of operation, signatures, reliability, maintainability, survivability, and logistic burden. In addition, the report will discuss the pros and cons associated with fueling the selected systems and the anticipated fuels for the given period.

APPENDIX B

COMMITTEE MEETINGS AND SITE VISITS

1) Committee Meeting, July 1-2, 1987, Washington, D.C.
   - Presentations made by the following from the Ft. Belvoir Research, Development, and Engineering Center:
     - Johann Joebstl
     - Alois Jokl
     - Ashok Patil
     - Richard Sale
   - Presentations also made by:
     - Colonel Larry Bramlette, Office for Mobile Electric Power
     - Colonel Archie Doering, The Army Training and Doctrine Command
     - Michael Higgins, BDM Corporation
     - Leo Stabinoha, Southwest Research Institute

2) Site Visit, September 21, 1987, Ft. Belvoir, Virginia
   - Presentations made by:
     - David Baughm, Ft. Belvoir
     - Karl Berger, Ft. Monmouth
     - Samuel Cerami, Ft. Belvoir
     - Jerry Cichosz, Onan Corporation
     - Sol Gilman, Ft. Monmouth
     - Al Meredith, SAI Corporation
     - Jerry Wilson, Ft. Belvoir

3) Committee Meeting, September 22, 1987, Washington, D.C.
   - Presentations made by:
     - Richard McClelland, U.S. Army Tank Automotive Command
     - Charles Weitz, General Motors Corporation
     - Bic Zaidell, General Motors Corporation

4) Committee Meeting, November 5-6, 1987, Washington, D.C.
   - Presentations made by:
     - William Beale, Sunpower, Inc.
     - Eugene Ecklund, U.S. Department of Energy
     - Georges R. Garinther, U.S. Army Human Engineering Laboratory
     - Robert W. Schleicher, GA Technologies, Inc.
     - Henry L. Stadler, Jet Propulsion Laboratory

5) Committee Meeting, December 15, 1987, Washington, D.C.
   - Presentations made by:
     - Everett Arnold, Detroit Diesel Allison
     - Dan Cummings, John Deere International, Inc.
     - William Fiegart, John Deere International, Inc.
     - Frank Shields, U.S. Army Center for Night Vision and Electro-optics
     - David Swanson, AVCO Research Laboratory

6) Committee Meeting, January 28-29, 1988, Washington, D.C.
Presentations made by:
Graham Aspin, Rolls-Royce, Inc.
Ronald Brien, Rolls-Royce, Inc.

7) Committee Meeting (working group), March 31-April 1, 1988, Washington, D.C.

8) Committee Meeting (working group), June 2-3, 1988, Washington, D.C.

9) Individual committee members visited:
Briggs and Stratton Corporation, Wauwatosa, Wisconsin
Yanmar Diesel Company, Ltd., Anaheim, California

10) There were also informal discussions with:
Teledyne Energy Systems, Timonium, Maryland
Teledyne Continental Motors, Mobile, Alabama

APPENDIX C

ELECTRIC GENERATORS

Recent developments in power electronics and permanent magnet materials suggest a re-examination of basic design options for field power generators. Specifically, can significantly smaller generators be developed to produce the desired output power using multiple phases or higher rotor speeds, or both, and can modern power electronics be utilized to convert the resulting output to 60 Hz single phase? The following is admittedly a simplified analysis to illustrate the relationship between speed and power density.

POLYPHASE GENERATORS

A generator armature is more efficiently utilized as the number of phases is increased. As an example, consider a four-pole generator rotor with 24 slots (six slots per pole). The voltages induced in the twelve pairs of slots form a star with 12 equally-spaced vectors, shifted in this example by 36° with respect to each other (Figure C-1).

These slot voltages add vectorially to give the phase voltage. For a single phase connection (Figure C-2), the phase voltages are given by:

$$|\overline{AG}| = \overline{AB} + \overline{BC} + \overline{CD} + \overline{DE} + \overline{EF} + \overline{FG}$$

$$\text{or } |\overline{AG}| = 3.86\ |\overline{AB}|$$

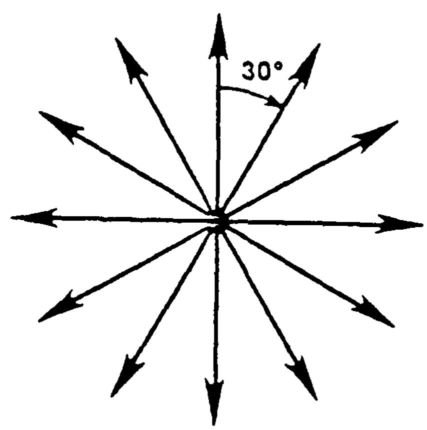


FIGURE C-1 Slot voltages of example rotor.

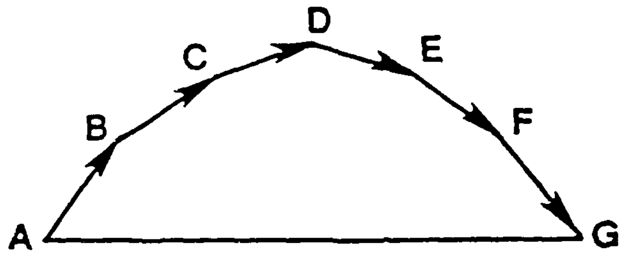


FIGURE C-2 Addition to slot voltages to produce phase voltages.

Recalling that the output power is the instantaneous product of voltage, current, and number of phases, the relative output power for any number of phases up to six can be determined (Table C-1).

TABLE C-1 Generator Output as a Function of Number of Phases (Vs is voltage produced by one slot pair)

No. of Phases	No. of Slot Pairs per Phase	Output Power	Relative Output Power
One	Six	3.86 $V_sI\cos\phi$	1.00
Two	Three	5.48 $V_sI\cos\phi$	1.42
Three	Two	5.79 $V_sI\cos\phi$	1.50
Six	One	6.0 $V_sI\cos\phi$	1.55

From this example, it can be seen that an increase in output power of some 50 percent can be realized by changing from single phase to polyphase configurations and that the bulk of the increase is realized at three phases.

POWER AS A FUNCTION OF ELECTROMAGNETIC AND MECHANICAL PARAMETERS

The output power of a generator can be expressed as

$$P = mVI$$

where M = number of phases
I = machine current (per phase)
V = machine RMS voltage (per phase)

additionally $V = \sqrt{2}\,\pi\;\Phi f k_n N$

where Φ = flux per pole
f = electrical frequency
k_n = winding factor
N = number of turns per phase

$$\Phi = \underbrace{\frac{2}{\pi}}_{\text{coefficient for sinusoidal distribution}} (B_\delta \tau l)$$

$$f = \frac{p\omega}{2\pi}$$

where B_δ = is defined below
τ = polar pitch = $\frac{\pi D}{2p}$
l = active length of winding
$2p$ = number of poles
ω = rotor angular velocity (rad/sec)

A is the armature current loading (current per unit circumference)

$$A = \frac{2mIN}{\pi D} \left(\text{A/m}\right)$$

$$P = \frac{\pi k_n}{2\sqrt{2}} \underbrace{\left(2p\Phi\right)}_{\text{total flux}} \underbrace{\left(\pi DA\right)}_{\text{total current}} \frac{\omega}{2\pi}$$

let $n = \frac{\omega}{2\pi}$ = REV per sec

$$P = \frac{\pi^2 k_n}{\sqrt{2}} D^2 l A B_\delta n$$

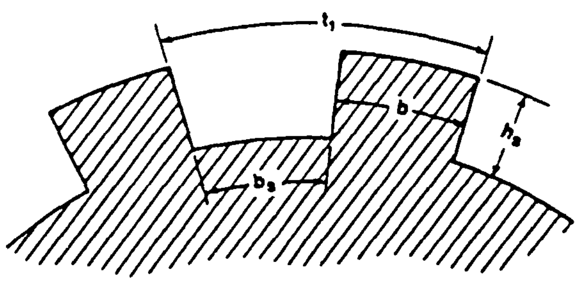


FIGURE C-3 Slot detail.

$$\text{Current Density, } J = \frac{A\, t_1}{h_s\, b_s\, k_{cu}}$$

where $k_{cu} \equiv$ copper packing factor

$$B_\delta = B \frac{b}{t_1} k_{FE}$$

where $B =$ average tooth flux density
$K_{FE} \equiv$ iron packing factor (axially)

then

$$P = \frac{\pi^2 k_n}{\sqrt{2}} \left(k_{cu}\, k_{FE} \frac{b_s}{t_1} \frac{b}{t_1} \right) h_s\, (D^2 l)\, (JB)\, n$$

$$P = \sqrt{2} \left(k_n\, k_{cu}\, k_{FE} \frac{b_s}{t_1} \frac{b}{t_1} \right) h_s\, (\tau^2 l)\, (2pf)\, (jB)$$

from this we can derive the following scaling relationships.

$$P \propto L^4 n$$

where L is the linear dimension

or $L \propto P^{1/4}$

weight $\propto L^3 \propto P^{3/4}$

losses $\propto L^3 \propto P^{3/4}$

$$\text{efficiency } \eta = 1 - \frac{\text{lossses}}{p}$$

$$= 1 - \frac{\text{constant}}{p^{1/4}}$$

This suggests no advantage in power output by increasing frequency by increasing the number of poles but a direct gain in power output by increasing the rotational speed. In actuality, there is some gain in increasing the number of poles but not as significant as the gain from increased speed. Furthermore, the use of exotic material such as Permendur in small quantities to form the slots between teeth could be useful in increasing the output power of generator designs.

APPENDIX D

GAS TURBINE ENGINES

Starting in the 1940s, gas turbines have been used in airplanes because of their high power density. This original application of the gas turbine to aircraft was driven by the need to have both a light-weight and low-volume power plant. Gas turbines have generally been developed in power ratings greater than 300 kW but recently there have been increased efforts in the range of 50 to 300 kW.

Unlike the intermittent-combustion engines, the gas turbine operates as a steady-flow machine (Figure 4-2). Combustion air enters the engine through a centrifugal compressor where the pressure is raised from 4 to 35 atmospheres, depending on the load and the engine design. Part of the air is sprayed and burned. Additional air is introduced into the secondary and dilution zones of the combustor to reduce the temperature of the gases entering the turbine.

The gases then pass through the turbine where work is developed. Part of this work is used to run the compressor while the remainder is delivered to the load on the engine. If the exhaust gases pass out of the turbine without a heat exchanger, the turbine is referred to as a simple-cycle engine. Regeneration is commonly used in gas turbines where improved part-load fuel economy is desired. Today's gas turbines typically operate at 1040 to 1095°C (1900 to 2000°F) for metal engines and developments of 1370°C (2500°F) are in process for the automotive gas turbine engines that use ceramics or specially cooled blades. Gas turbines have been developed to run on liquid, gaseous, and solid fuels. One of the advantages of the application of gas turbines to MEP units is its high speed (30,000 to 50,000 rpm) capability.

GAS TURBINES IN CURRENT DEVELOPMENT APPLICABLE TO MOBILE ELECTRIC POWER (MEP) UNITS

The U.S. Army has gas turbine MEP units that provide power for the Patriot Missile System. The engine is a 150 kW, Allison Model 404 regenerative turbine engine with two shafts. This engine has successfully passed all U.S. Army required performance and reliability goals. The low pressure

ratio of the aluminum compressor is four to one, a single diffusion flame combustor operates at 1024°C (1875°F) and the combusted gases expand through a gasifier turbine (which drives the compressor) and a power turbine (which drives the electric generator). The exhaust gases from the power turbine pass through two rotary regenerators (732°C [1350°F] maximum into the regenerator and 177°C [350°F] minimum out of the regenerators) to an exhaust stack for the engine. The heat picked up in the high efficiency (86 to 92 percent efficiency) rotary regenerator is delivered to the inlet of the combustor by the compressor discharge air, which passes through the regenerator and increases the combustor inlet temperature. The heat recovery in the rotary regenerator improves the gas turbine efficiency significantly.

Other examples of prototype regenerative gas turbines are the single shaft Garrett Turbine Engine Company AGT101, and the Allison two shaft AGT100 engine, both research prototype engines. Each of these regenerative engines are designed to operate at turbine inlet temperatures of 1288°C to 1370°C (2350° to 2500°F), at 75 kW (100 hp) and develop specific fuel consumption (sfc) values at 0.31 to 0.33 lb/bhp-hr (189 to 201 g/kwh) as compared to 0.44 lb/bhp-hr (268 g/kwh) for the Allison 404 engine. Also, the 100 hp AGT101 engine runs at 100,000 rpm and the AGT100 runs at 85,000 rpm. Appropriate gearing reduces these engine speeds to automotive transmission speeds (reduction ratios of 22:1 or 30:1). Although not achieved as yet, both the AGT101 and the AGT100 engines are designed to achieve fuel economy 30 percent better than automotive gasoline engines (16 percent better than automotive diesel engines). Ceramic hot flow path components made of structural silicon nitride, silicon carbide, sialon, ceramic composites (such as silicon carbide whiskers in a silicon nitride matrix) and aluminum silicate regenerators with lithium-aluminum-silicate flow path shells are necessary for successful achievement of the AGT100 and AGT101 performance goals.

An additional turbine being developed for the U.S. Army is the Garrett GTP50 and the Turbomach Multipurpose Small Power Unit (MPSPU) engine. The Garrett GTP single-shaft, simple-cycle engine is being developed at 37 kW (50 hp) with growth capability to 56 kW (75 hp) and perhaps to 75 kW (100 hp) in the mature engine. The emphasis in this turbine engine had been light weight, low cost, high reliability and maintainability. The fuel economy is not as crucial for the intended APU applications of the MPSPU engine. These different engines illustrate that powerplant application emphasis can change weight, cost, fuel economy and other characteristics of turbine engines.

FUTURE DEVELOPMENTS

Power and Inlet Turbine Temperature

Emergence of high-temperature materials for use in gas turbines is of extreme importance. Figure D-1 shows a plot of sfc versus shaft

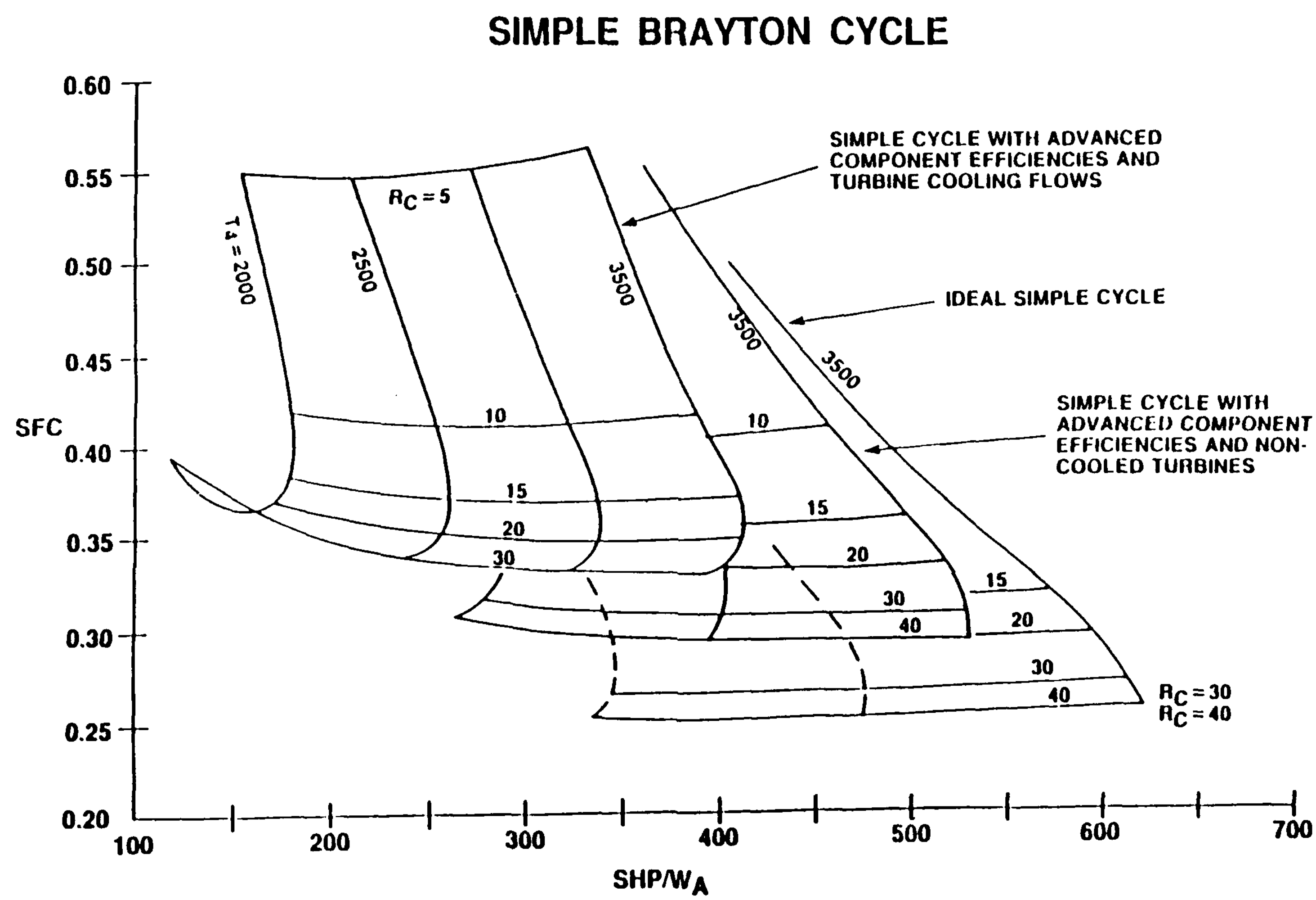


FIGURE D-1 Specific fuel consumption vs. power for a simple-cycle gas turbine.

horsepower per pound of airflow per sec (SHP/Wa) for various compressor pressure ratios (R_c) and operating turbine inlet temperatures (T_4 or T.I.T.) for simple-cycle gas turbines. Similarly, Figure D-2 shows a plot of sfc versus SHP/Wa for various R_c and T_4 values. Note that optimum R_c is low for recuperated turbines and high for simple-cycle turbines. Since airflow determines turbine diameter (with other parameters), it is observed that turbine overall size can be cut significantly (1/2 to 2/3) by varying turbine inlet temperature or by varying both R_c and temperature. Much emphasis has been placed on achieving high R_c turbine aerodynamic capabilities in the past. As a consequence, fairly mature aerodynamics now exist for turbine engines. Furthermore, the true potential for improved materials continues to be identified, which can significantly elevate turbine working temperatures. Materials such as silicon nitrides and silicon carbides have now been developed to make uncooled turbine components. Ceramic composite materials are also receiving large support for development into useful components for engines and other structures. The developments for the National Aerospace plane (NASP) and Strategic Defense Initiative (SDI) coupled with many other uses will help the gas turbine operating temperatures move from the 1093^{o}C (2000^{o}F) left hand ordinate toward the 1925^{o}C (3500^{o}F) right hand side of Figures D-1 and D-2 with corresponding reductions in turbine size coupled with improved fuel consumption in the years 1990 through 2015. Probably no other powerplant has as much to gain as the gas turbine from these types of material improvements.

GAS TURBINE FUEL FLEXIBILITY

The gas turbine engine has a unique capability to burn (oxidize) fuel in practically any form. Turbines with simple and regenerated cycles that burn natural gas, the JP fuels (JP-4, 5, 8), diesel fuel, methanol and dry micronized coal have been demonstrated. Changes to the fuel systems are required for transition from gaseous to liquid fuel (changes to pumps and fuel nozzles) and from liquids to dry micronized coal (or coal water slurries) in the turbine engine. This multi-fuel capability is only shared with the Stirling engine. While the Army thrust is toward uniform fuel at the present time, one can easily identify scenarios in which a variety of liquid or gaseous fuels could be available in newly captured territory or in an ally's inventory: MEP units could be either delayed or inoperable at critical times, such as for missile system detection or firing, because of the inability to operate on plentiful supplies of either gasoline, alcohol or natural gas, while diesel fuel is in transport to the user. Hence, multifuel capability is a desirable feature for MEP systems.

GAS TURBINE SIGNATURE CHARACTERISTICS

The gas turbine noise generated comes from multiple sources. The operating speed of a single- or two-shaft turbine is generally above 35,000 rpm for the 200 kW size MEP unit, above 95,000 rpm for the smaller

SINGLE SPOOL, FREE POWER TURBINE TURBOSHAFT
SEA LEVEL STATIC STANDARD DAY
RECUPERATIVE (η_R = 90%, ΔP_r = 5%)

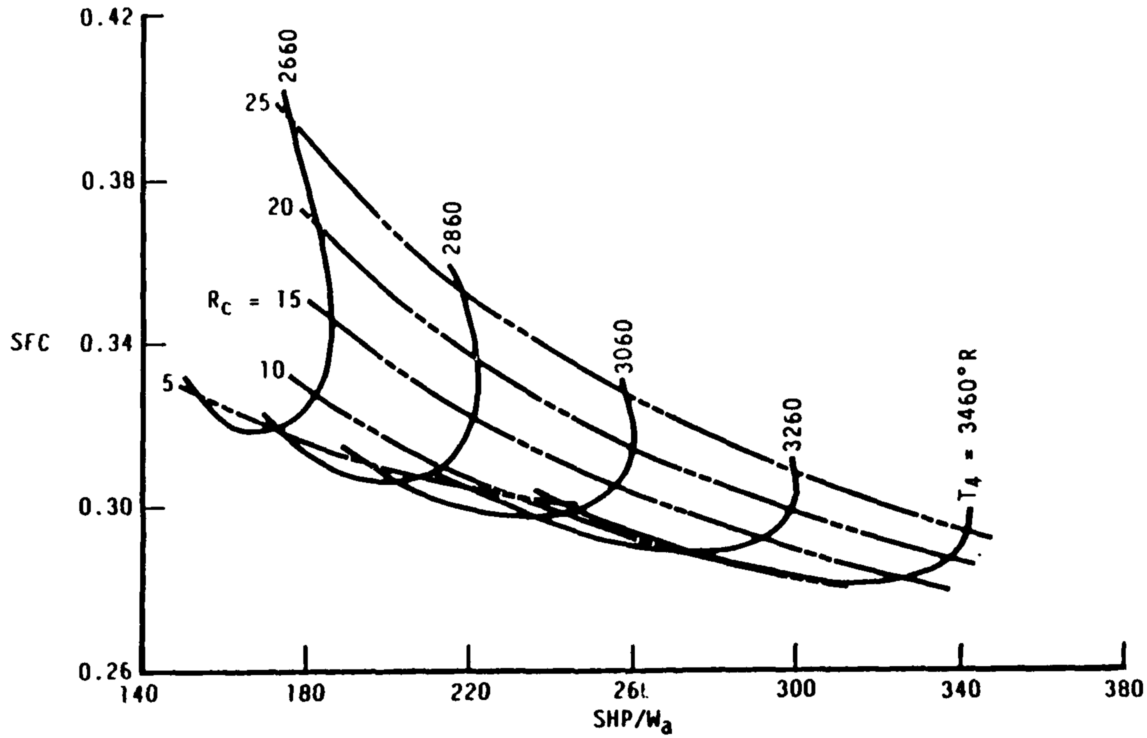


FIGURE D-2 Specific fuel consumption vs. power for a gas turbine (recuperative).

size MEP units (60 to 150 kW), and above 100,000 rpm for 10 kW to 50 kW MEP units. Thus, noise generated by compressor or turbines would start at 600 Hz (36,000 rpm) and rise to 1,000 Hz (60,000 rpm) and to 2,000 Hz (120,000 rpm) for the smallest size turbines. This contrasts to 60 Hz to 200 Hz for diesel and gasoline engines. As with reciprocating engines, gear boxes, nonuniform combustion, hydraulic pumps and other non-engine features can produce other noise frequencies. Gas turbines generally produce higher frequency, less audible, more easily attenuated frequencies than reciprocating engines at similar power levels.

Figure D-3 shows a plot of mobile generator set noise for both simple-cycle and regenerated-cycle gas turbine engines. The regenerated-cycle engine is probably easily suppressed to the aural detectability limit of 65 dBA while the simple-cycle engine would require significantly greater suppression material to reach the same sound level.

Figure D-4 shows the 1/3 octave sound pressure level in dB versus 1/3 octave band center frequency for both simple-cycle and regenerated-cycle engines. The low sound pressure level (SPL) in decibels (dB) levels at low frequencies (most difficult to suppress) is noted. The frequency spectrum shown (labeled Patriot-150 kW) is a current U.S. power generator set.

The turbine exhaust temperature is important to assess infrared (IR) signature. Typically, simple-cycle turboshaft engines have exhaust gas temperatures from 415°C to 593°C (780° to 1100°F); 525°C Average [980°F]) depending on power level and design. This level constitutes significant IR signature and would require an extremely efficient IR suppression device. The regenerated gas turbine will have exhaust gas temperature that varies from 104°C (220°F) at idle to 260°C (500°F) at maximum power. This level of exhaust temperature would probably be easily obscured by simple shields or carefully selected exhaust discharge orientation on the MEP set.

The final signature from turbines relative to detection from advanced sensors, would be pollutant emissions. Naturally, fuel selection and combustor design is important in determination of emissions.

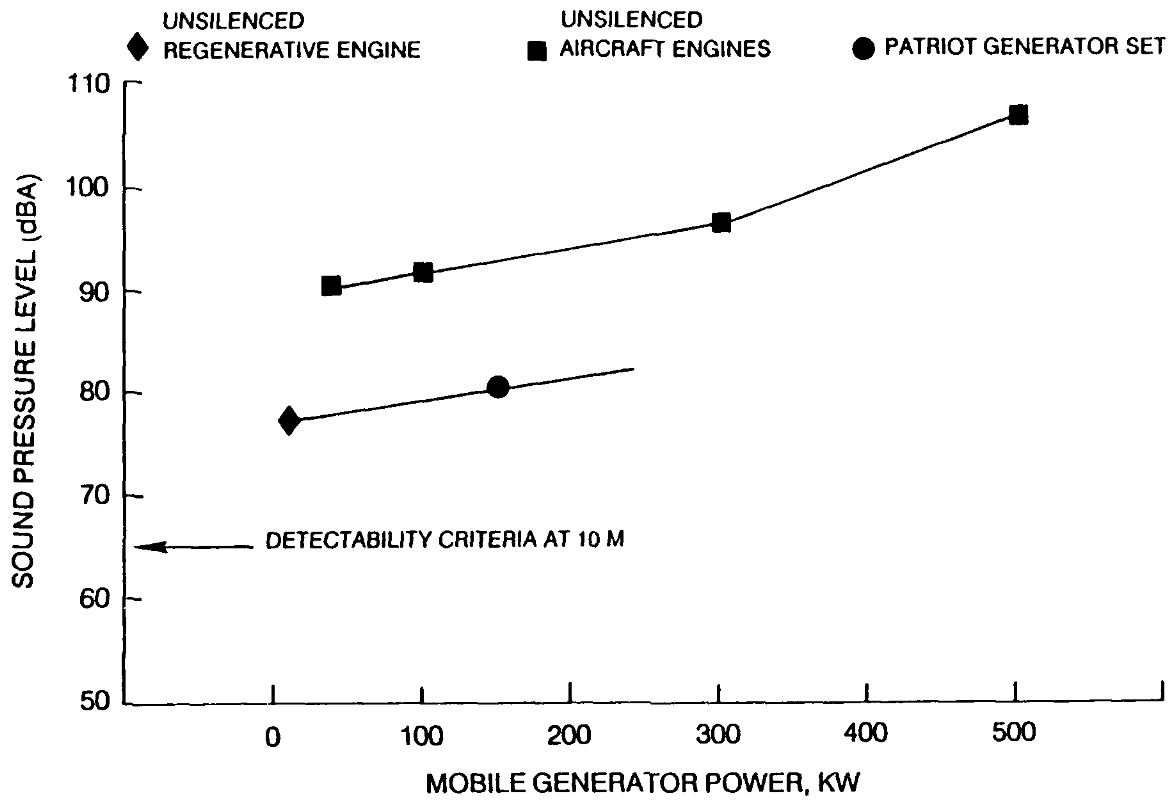


FIGURE D-3 Gas turbine noise as a function of power.

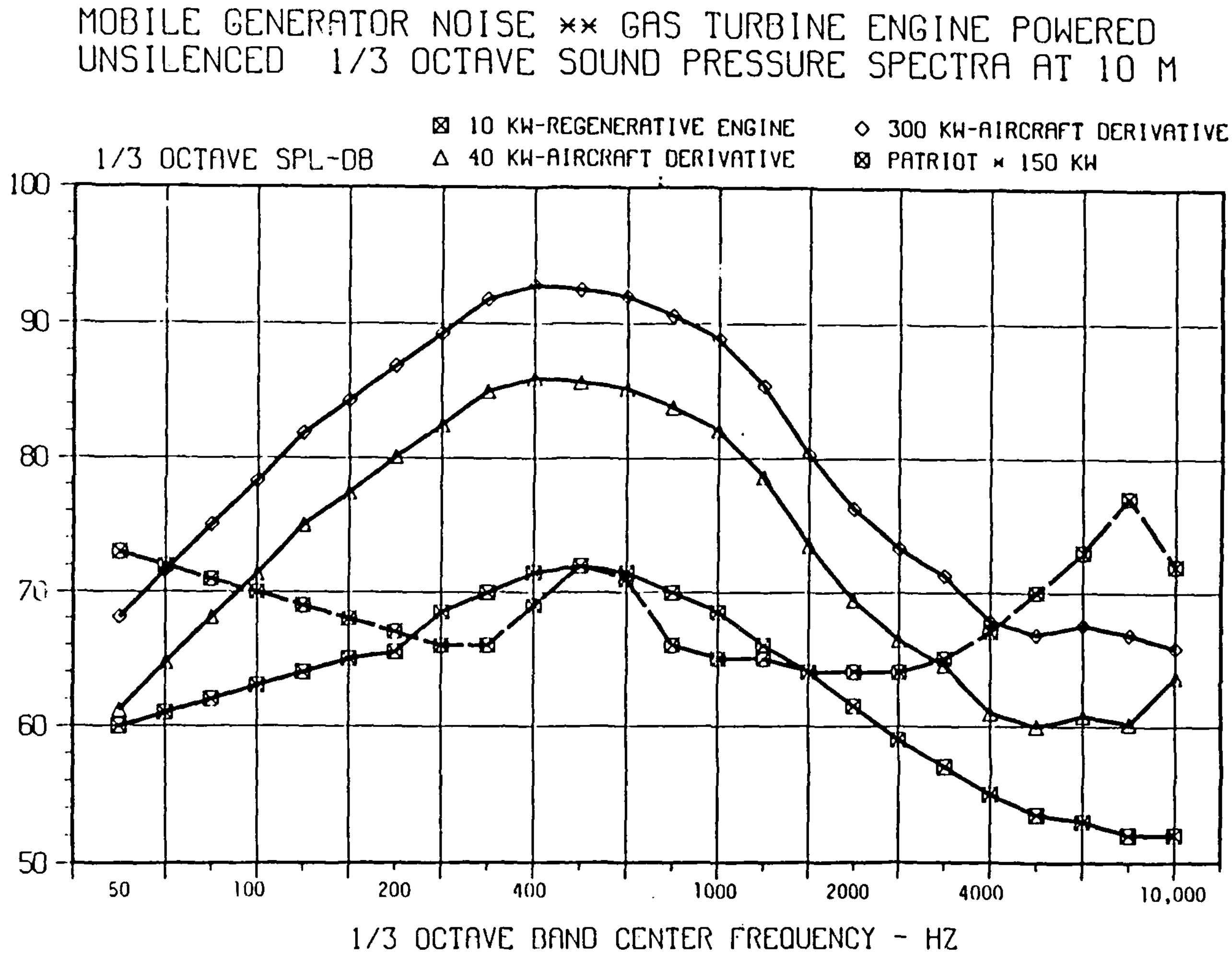


FIGURE D-4 Gas turbine noise frequency spectra.

APPENDIX E

STIRLING ENGINES

The Stirling engine was invented in Scotland in 1816, and was used until the steam engine became the dominant engine because of its high power in an engine of a given size. In about 1937 N. V. Philips of the Netherlands started work on the modern Stirling engine. In contrast to Stirling's original engine, which operated with air at atmospheric pressure, the modern engine operates with a low molecular weight gas, hydrogen or helium, at high pressures in the order of 1,500 to 3,000 psi.

The major components of the modern Stirling engine are (Figure E-1):

1. Power piston
2. Displacer
3. Compression space in the cylinder
4. Gas cooling heat exchanger
5. Thermal regenerator
6. Gas heating heat exchanger
7. Expansion space in the cylinder

The operation can be idealized as a four-part cycle with discrete motions of the piston and displacer. In the first step, Figure E-1a to b, the gas in the compression space is compressed by the motion of the piston. In the second step, Figure E-1b to c, the displacer moves down and the gas flows through the cooler, regenerator and heater. As the gas flows it is heated in the regenerator and the heater and enters the hot expansion space at the high temperature for the engine. The heating of the gas in the confined space of the engine causes a pressure rise above that resulting from the previous compression. In the third step, Figure E-1c to d, the power piston moves down expanding the high pressure gas. In the fourth step the displacer moves up and the gas flows through the heater, regenerator and cooler. As the gas flows it is cooled in the regenerator and cooler and enters the cold compression space at the lowest temperature for the cycle. Power is produced by the cycle because the gas is expanded while hot and at high pressure and is recompressed while cold at low pressure. In a real engine the motions of the piston and displacer are continuous rather than discrete as in this simple illustrative example. The motions are usually sinusoidal with the displacer motion leading the piston by about 90 degrees.

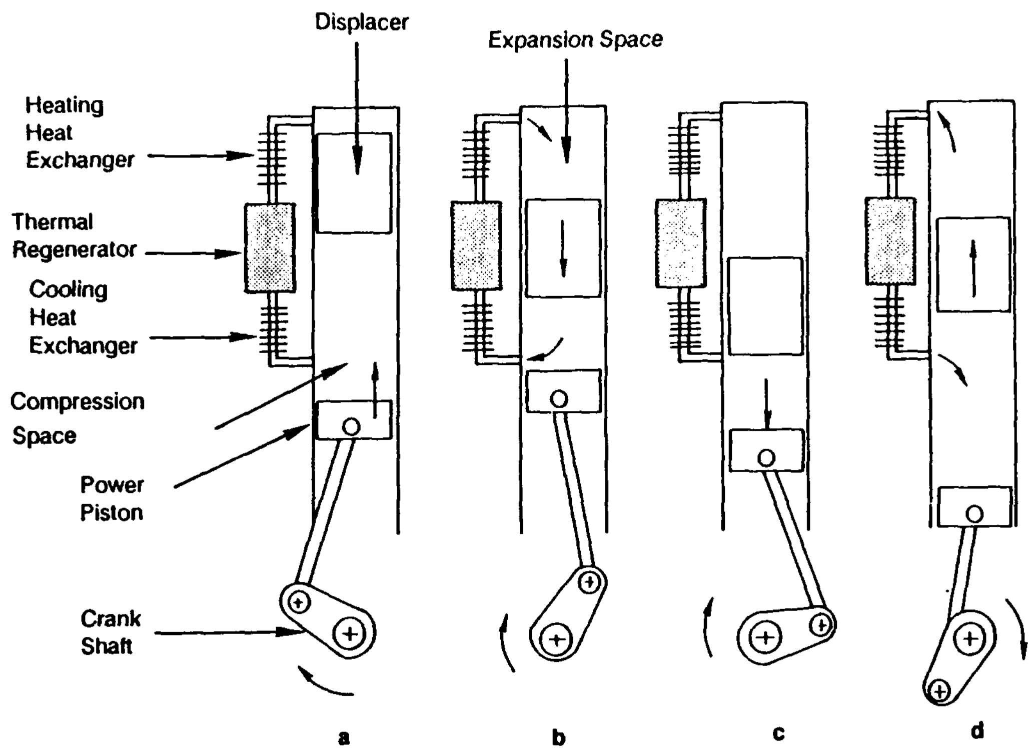


FIGURE E-1 Basic Stirling Engine operation.

A wide variety of mechanical mechanisms have been invented to provide the piston and displacer motions for the Stirling engine. These mechanisms can be grouped into two classes, kinematic and free piston. In the kinematic engine the motions are geometrically prescribed, for example, by a crank and connecting rod mechanism. Others use cam and lever mechanisms. The wide variety of arrangements have been cataloged by Walker (1980) in his book on Stirling engines. In the free piston Stirling engine the motion of the piston and displacer is determined by the gas pressures and the inertia of the moving masses together with the load forces. In essence, the piston and displacer bounce on springs (usually gas springs) and the power is taken out by coupling to the oscillating pressure or by coupling electromagnetically to the oscillating motion of the piston (see Figure E-2.

HISTORY OF DEVELOPMENTS

When Philips began the development of the modern Stirling engine one of the intended applications was a power source for mobile electric power sets. The Philips work, which was interrupted by World War II, continued after the war and the results were published (Rina and de Pre, 1946; De Brey and Van Weenen, 1947-48). Philips also developed and built a number of small mobile electric power generating sets employing a small Stirling engine, but these units never found a market. This work also led to the development of a line of cryogenic refrigeration products. By the early 1950s Philips had completed the development of the Philips Stirling cryogenic refrigerator (Kohler and Jonkers, 1954-55a,b) based on the Stirling cycle engine operating on the reversed cycle. These machines, now known as Philips Cryogenerators, continue to be a viable commercial product.

The Philips Stirling engine program under the direction of Dr. R. L. Meijer developed the engine to a high degree using a rhombic drive mechanism (Meijer, 1958-59). They were not successful in finding any market for their well-developed engines. Wide ranging applications were investigated, including torpedo propulsion, space power, boat engines, submarine engines, bus engines and automotive engines. By the 1960s, Philips started licensing the Stirling technology to regain something from their development investment. The first licensee in the United States was General Motors (GM). GM used the well developed thermal design technology from Philips and concentrated on reducing the very high manufacturing cost of the Philips designed engines for automotive applications (Heffner, 1965). One product of the GM program was the GPU-3 (ground power unit) generator set that was developed in 1963. Only a few experimental units were actually built by GM and these were not thoroughly tested at that time. Later, the National Aeronautics and Space Administration (NASA) Lewis Research Center restored one and thoroughly tested one of these units. The design and test results for this Stirling engine are one of the few useful results to be published in the open literature (Cairelli et al., 1978). After a number of years GM decided that the Stirling engine was not competitive in their markets and they ended the Stirling engine program and the arrangement with Philips.

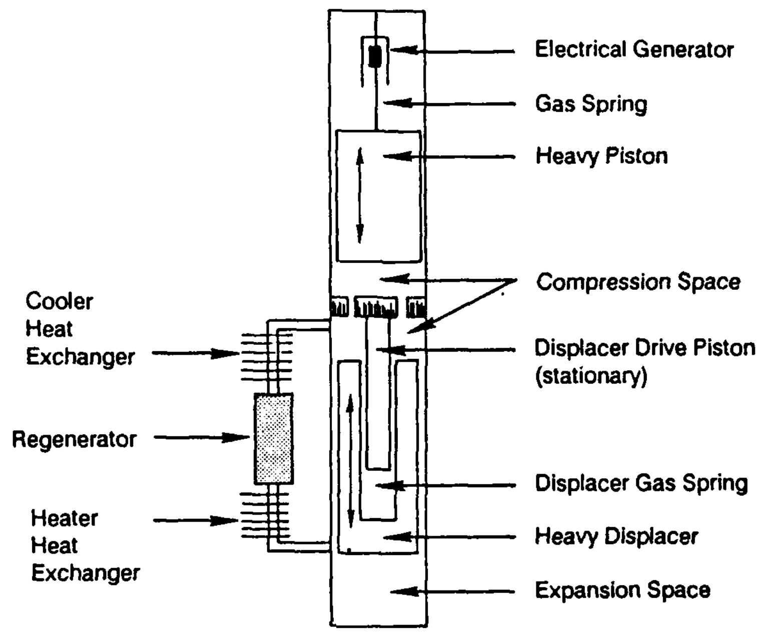


FIGURE E-2 Simplified schematic of a free-piston Stirling engine.

In 1970 Ford Motor Company and Philips joined in a program to investigate the applicability of the Stirling engine to passenger cars. By 1972 Ford was the world-wide licenser of the Philips engine for virtually all applications. The Ford-Philips 4-215 wobble plate Stirling engine employing four double-acting cylinders was developed under this program (van Giesel and Reinink, 1977). Philips built two of these Stirling engines that were installed in Ford Torino automobiles. These cars together with an older Philips Stirling-engine powered bus were demonstrated in Dearborn, Michigan in 1976. In 1977 a U.S. Department of Energy (DOE) Stirling engine development contract was awarded to Ford in support of the automotive program. In spite of this progress Ford discontinued its involvement with Stirling engines in 1978. A year later Philips ended its Stirling engine activities and sold the technology to a new company, United Stirling of Sweden (USS).

The Automotive Stirling engine development program was then funded by DOE through a prime contract to Mechanical Technology Inc. (MTI). The project was based on a team approach, with USS supplying the basic engine design technology; AM General (AMG), a subsidiary of American Motors for vehicle-engine integration; and MTI as the prime and systems contractor. The objectives of the program included a 30 percent improvement in the combined fuel economy based on predictions for a 1984 production vehicle (MTI, 1979). The first engine of the program was the United Stirling P-40 engine. The second was the MOD I engine designed by MTI and the third the MTI MOD II engine. Over the past 10 years this $100 million program has involved the efforts of several government agencies including NASA, DOE, the U.S. Department of Defense (DoD; that is, the Air Force and the Army) and about 30 subcontractors. The best steady-state efficiency achieved by the Mod I engine has been about 40 percent at part load and about 27 percent at full load.

The invention of the basic free piston Stirling engine is usually attributed to W. T. Beale (1969, 1971). Similar engines were invented by Cooke-Yarborough et al. (1974). The attractive potential advantages of this free-piston engine are its mechanical simplicity and hermetic sealing when coupled to a reciprocating electric generator. Thus, these engines are attractive for applications that require high efficiency, high power density, long life, high reliability, and low vibration and noise. Work has been done on free-piston engines for generating solar electric power, space electric power from nuclear sources, and engine driven heat pumps for residential heating. Work on a free-piston Stirling driven air conditioner was reported by Beale et al. (1975). Goldwater and Morrow (1977) described a free-piston Stirling generator. In 1982 the Oak Ridge National Laboratory and the NASA Lewis Research Center undertook a joint program to develop the generic technology of free-piston Stirling engines applicable to both space power and terrestrial applications (Schreiber, 1985). The free-piston Stirling generator is also being investigated as part of the SP-100 Space Reactor Power Program initiated in 1983 by NASA, DoD, and DOE. The focus of this program has been the design and construction of the Space Power Demonstration Engine at MTI. A general description of this engine is given by Slaby (1987), and more recently by Tew (1987a,b). The engine is currently undergoing extensive testing at Lewis and at MTI. Sun Power Inc. (Athens, Ohio) is also designing a free-piston linear alternator

engine under this space power program (Beale, 1987) and a free-piston unit for the U.S. Army, Fort Belvior (Beale, 1987; Berchowitz et al., 1987).

ASSESSMENT OF THE STATE OF STIRLING ENGINE TECHNOLOGY AND FUTURE DEVELOPMENTS

Development of the Stirling engine has continued off and on for about the last 50 years as described in the previous section. In spite of this long development the engine has not found any significant application market. The reversed Stirling cycle is, however, widely used for cryocoolers.

Most of the development effort has been on the kinematic crank and piston-displacer engine for automotive applications where shaft power is required. In recent years attention has turned to the free-piston Stirling engine to simplify the mechanism and to allow hermetic sealing. Power output is from a linear reciprocating generator within the engine enclosure or is provided by coupling to the periodic pressure of the engine.

At the present state of development the kinematic engine operating on hydrogen at high pressure is competitive with internal combustion engines in efficiency and power density. It is not competitive in cost. It can be a very low noise power plant if the burner and cooling air systems operate at low air velocities. Although the basic Stirling engine is relatively simple, the addition of the burner, cooler, and power control systems brings complexity that is comparable to other power plants. The requirement to seal the operating hydrogen or helium for long periods is unique to the engine. Kinematic engines with the generator inside the hermetic enclosure of the engine have not been developed.

The free-piston Stirling engine has not yet reached the efficiency or the power density of the kinematic engine with a conventional rotary electric generator. Experience with the free-piston engine is more limited and the design analysis is more complex. The experience factors in the design codes are not as well established as for kinematic engines. The control of the piston and displacer strokes under varying loads is a part of the problem. Very rudimentary methods are used at present (Berchowitz et al., 1987). However, better methods are projected but are not yet available for review. Another part of the problem is that linear generators are unconventional and the designs do not have the benefit of years of evolution.

The major impediment to improved performance of Stirling engines is high temperature materials. For higher efficiency and increased power density the temperature of the hot parts of the engine must be increased. To be economically competitive the cost of the fabricated hot parts must be reduced.

The large cost associated with a major Stirling engine development program for MEP applications appear to be beyond the cost-effective limit. This assessment is based on the large expenditures to date for all Stirling engine development, which have not produced any viable engines. Stirling engines of the free-piston type may become well developed for space power applications. This would set the stage for application of Stirling engines to MEP sets in the future. A breakthrough in low-cost high-temperature structural materials could well change the prospects for economically viable engines but the chance that low-cost, high-temperature materials that have sufficient high-temperature strength can be developed is low.

APPENDIX F

FUEL CELLS

A fuel cell is an electrochemical energy converter akin to a battery, but unlike the latter, its two electrodes consume an externally supplied fuel and oxidant, whereas in a battery the electrodes are consumed. For example, in the familiar zinc alkaline battery, the negative "fuel" electrode is the zinc itself, and the positive oxidizing electrode is manganese dioxide. Both are consumed as the battery discharges. The fuel, normally pure or impure hydrogen, is continuously fed as required to the negative fuel cell electrode, and the oxidant (oxygen in air in terrestrial fuel cells) is similarly fed to the positive. The electrodes have porous, high-surface-area structures that allow the greatest possible contact between active reaction sites, the electrolyte, and the gaseous reactant. Each cell consists of the two electrodes supplied by gas channels on their back sides, with an immobilized electrolyte layer between them. The cells are normally flat, and gas-channel material is electronically conducting so that cells can be separated by impervious, conducting bipolar plates, and can thus be assembled in series in the manner of a Volta Pile. This pile of thin (5 mm or less) fuel cell elements is called a stack (Figure 4-3). This is the most effective electrical connection arrangement, since it reduces internal resistance to a minimum. Means must be provided to allow adequate gas manifolding and allow exit of the reaction product (water or steam), as well as to provide cooling. The dc output from the stack is used directly or converted to ac using a solid-state inverter.

Fuel cells are classified by the electrolyte used, which can be acid or alkaline, molten carbonate, or solid oxide, depending on the application. Acid electrolyte cells presently use either phosphoric acid (Appleby, 1983; 1986) or a fluorinated sulfonic acid polymer (Appleby and Yeager, 1986) electrolyte, such as DuPont Nafion^{R} (PAFC, SPE systems). Alkaline cells (AFCs) use aqueous potassium hydroxide electrolyte (Bockris and Appleby, 1986). Molten carbonate fuel cells (Selman, 1986) (MCFC) operate at 650°C using a mixed lithium-potassium carbonate electrolyte, and the doped-zirconia solid oxide electrolyte fuel cell (SOFC) requires a temperature of 1000°C to show adequate conductivity (Brown, 1986).

Since fuel cells operate by converting the free energy of combustion of the fuel (usually hydrogen) directly to electricity, their maximum

theoretical voltage corresponds to the fuel energy of the reaction expressed in electron-volts (ev). This falls with operating temperature from 1.23 V at 25°C to under 1.0 V at 1000°C. However, this is largely compensated by lower losses as the temperature is raised. Hence, hydrogen-air systems operating at ambient pressure and at practical current densities (A/cm^2 of geometrical area) will often yield higher potentials in the high-temperature systems. Thus, a state of the art ambient pressure PAFC operating at its most effective temperature (200°C) will operate at 0.65 V and 0.2 A/cm^2, whereas a molten carbonate system will yield 0.78 V with ambient pressure reactants. The future compact "monolithic" SOFC, still in the laboratory stage, will yield 0.7 V at 0.5 A/cm^2, which is slightly better than the best state of the art alkaline system operating at 80°C. Typical performance curves (cell voltage and electrode polarization as a function of current density) are shown in Figure F-1. As can be seen, the major limitation in the low-temperature systems is the oxygen reduction reaction, which suffers from catalytic problems even when the most effective catalysts (e.g., high surface area platinum) are used (Appleby, 1974; Bockris et al., 1983). These catalytic problems disappear at higher temperatures, and the systems eventually become internal resistance limited.

CHARACTERISTICS AND FUELS

As discussed above, hydrogen is by far the most effective fuel for use in fuel cells of all types and sizes between several watts to multimegawatt units. This is because its catalyzed oxidation rates are very high, even at low temperatures (Figure F-2). With the exception of hydrazine (which can be eliminated as a fuel due to its hazardous nature and to transportation logistics), other combustible fluids (methanol, ammonia and organic fuels, in decreasing order of reactivity) show very low to negligible activity in lower-temperature systems. While a breakthrough in electrocatalysis allowing the direct use of conventional fuels within the time-frame to the year 2015 cannot be discounted, the possibilities for attaining this, based on past experience, are not very high. They will require not only a deeper understanding of the fundamental phenomena involved, but also the discovery of new classes of materials with special properties.

Failing such a breakthrough, a projection is limited to an extrapolation of today's fuel cell technology, which will operate most effectively on hydrogen (pure or impure), and much less effectively on direct methanol or direct ammonia. Direct hydrocarbon fuels have negligibly poor reaction rates at temperatures at which aqueous electrolytes can be used, and at high temperatures (molten salt or solid ion-conducting electrolytes) they crack irreversibly, producing coke-like carbon deposits.

Hence, at the present time, conventional fuels must first be converted to hydrogen before being oxidized in the fuel cell. Organic fuels for use

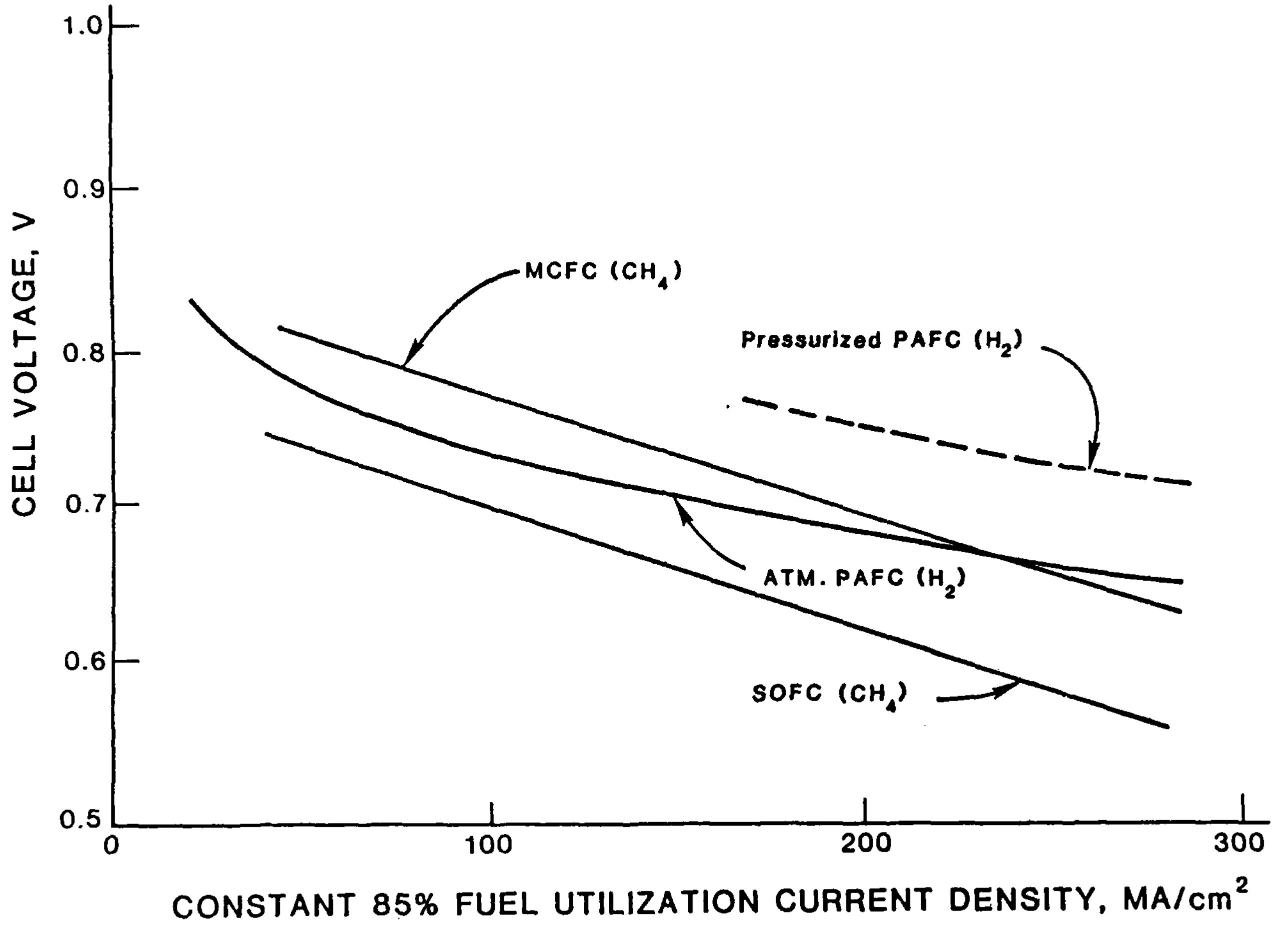


FIGURE F-1 Typical overall polarization curves (voltage-current characteristics) of different fuel cell types.

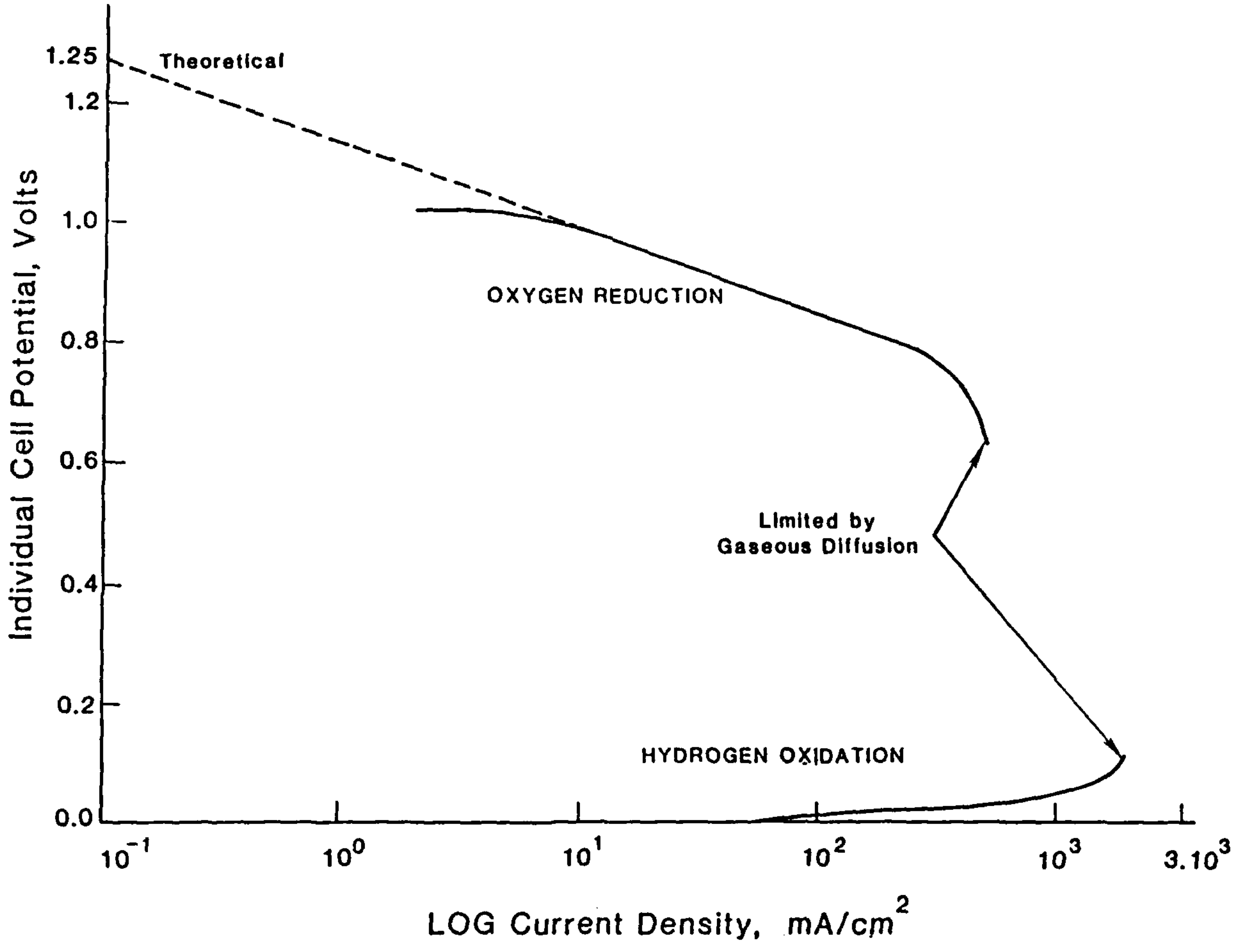


FIGURE F-2 Typical voltage-current characteristics of separate anode and cathode reactions in a phosphoric acid fuel cell.

with low-temperature fuel cells are treated to yield a mixture of hydrogen and carbon dioxide (CO_2). In spite of its high performance compared with the acid electrolyte systems, the alkaline fuel cell, therefore, is at a considerable disadvantage, since any carbon dioxide in the fuel supply will carbonate its electrolyte. This will result in high internal resistance and precipitation of carbonate in the porous electrodes, causing failure. Pure hydrogen is, therefore, the only practical fuel for alkaline systems, and air must be scrubbed to remove CO_2. In contrast, the other systems can operate on hydrogen-CO_2 mixtures from a fuel processor.

A further problem can be the presence of carbon monoxide (CO) in the fuel mixture. The maximum operating temperature of present SPE electrolytes is about 90°C under ambient pressure conditions, and the cell is then not CO-tolerant. In contrast, the PAFC operating at 200°C will tolerate up to about 1 1/2 percent CO even in the presence of traces of sulfur, before catalytic poisoning of the anode occurs. The MCFC and SOFC are always CO-tolerant, and can consume CO as fuel, especially in the presence of water vapor, when water-gas shift to hydrogen will occur.

FUEL PROCESSING

Fuels cells can be made to operate on ammonia, methanol, and light hydrocarbons if these fuels are converted to hydrogen in a suitable fuel processor. Steam reforming of methanol, and other light alcohols and hydrocarbons, can be accomplished by using waste heat from a suitable fuel cell operating above 100°C (e.g., the PAFC) to produce steam. In general, a steam-reformed methanol PAFC unit will be lighter and less complex than a natural gas unit. Preferred sizes for low-temperature methanol-reforming units are in the range of 70 to 200 kW.

If the fuel feedstock is a saturated hydrocarbon (for non-military stationary use typically natural gas or desulfurized naphtha), a much higher reforming temperature than for methanol is required. This may be as high as 800°C, necessitating the addition of high- and low-temperature water-gas shift reactors to reduce the CO concentration to acceptable levels causing no further polarization of the PAFC anode. This complicates the system, and results in much greater weight and volume than for a methanol-reformer unit.

In contrast to low-temperature methanol-reforming systems, the problem of heat transfer has been shown to make the design of a conventional steam reformer for low-molecular-weight hydrocarbons extremely difficult in sizes below about 12.5 kW, the scale of the experimental Gas Industry TARGET ("Team to Advance Research in Gas Energy Conversion") unit of the early 1970s. Preferred sizes are now in the 40 to 200 kW range. Forty kilowatt natural gas units are presently very heavy (about 3,640 kg [8,000 lbs]), although weight may be expected to be reduced in the future by the use of improved reforming technology and new lightweight stacks: a reasonable weight target may be 1,365 kg (3,000 lbs).

Reforming of JP-8 fuel is virtually impossible for fuel cells smaller than 40 kW, at least in those using conventional technology. The problems are the requirement for extensive desulfurization (under 1 ppm) if conventional steam-reforming catalysts are used, along with the difficulty

of fuel vaporization. If the fuel cannot be fully vaporized without cracking, conventional vapor-phase hydrodesulfurization cannot be used. In addition, the steam requirement for reforming heavier fuels is much greater than for light fuels, leading to lower reforming efficiencies. However, JP-4 class fuels, after appropriate desulfurization, can be reformed in large units using relatively conventional techniques in larger chemical processors. Newer reforming methods may lead to lighter and more compact PAFC systems using heavy diesel-type fuels in the future. Thus, the main problem for tactical applications is not that of the relatively mature PAFC fuel cell stack, but of the reforming process for heavy, sulfur-containing fuels in small units. Further research effort is required in this area.

In contrast to PAFCs, MCFC and SOFC units operate at sufficiently high temperatures to allow internal reforming of certain fuels within the anode chambers of the fuel cell stack itself, provided that suitable fuel-steam mixtures are supplied to the cell (Figure F-3). Internal reforming increases overall fuel processing efficiency from about 80 percent for a light-hydrocarbon PAFC unit to a value similar to that of a PAFC-methanol unit (close to 100 percent), giving higher overall system efficiency. For example, advanced MCFC and SOFC systems could yield 55 to 60 percent overall efficiency on light hydrocarbons, compared with 40 to 45 percent for the PAFC on such fuels. While the internal reforming MCFC is limited to methane and very light hydrocarbons because of its relatively low operating temperature (650^{o}C), the advanced SOFC may be able to consume heavier hydrocarbons with steam injection, provided that their cracking temperature is sufficiently high to avoid carbon disposition.

In the future, the trend will be towards processing heavier distillate fuels such as No. 2 and No. 4 fuel oils, and coal-derived liquids and finally JP-8 for military use. The technologies for processing gaseous fuels (such as natural gas) and light liquids (such as naphtha, methanol and ethanol) by steam reforming are relatively mature. Much work remains to be done for heavier fuels (Yound, 1980) especially on alternatives to conventional steam reforming, such as partial oxidation and pyrolysis.

SUMMARY AND DISCUSSION

There have been great recent improvements in the fuel cell state of the art. Fuel cell stacks are now lightweight power sources and significant further improvements can be expected. The fuel cell stack is a uniquely efficient converter, typically transforming hydrogen to dc power at 45 to 50 percent or greater higher-heating-value efficiency (53 to 60 percent lower-heating-value efficiency). It also has the advantage (apart from mechanical components such as blowers) of zero noise signature, and the infrared signature of low-temperature systems is negligible. It therefore has a number of unique advantages from the military viewpoint. However, its major disadvantage is its general requirement for hydrogen fuel that requires the use of a heavy, complex fuel processor if conventional fuels are to be used. This would be necessary for most military applications because of the adoption of JP-8 as a standard fuel.

International Fuel Cells alkaline systems operating at high temperature (150^{o}C) and pressure (200 psi) on cryogenic hydrogen and oxygen now give

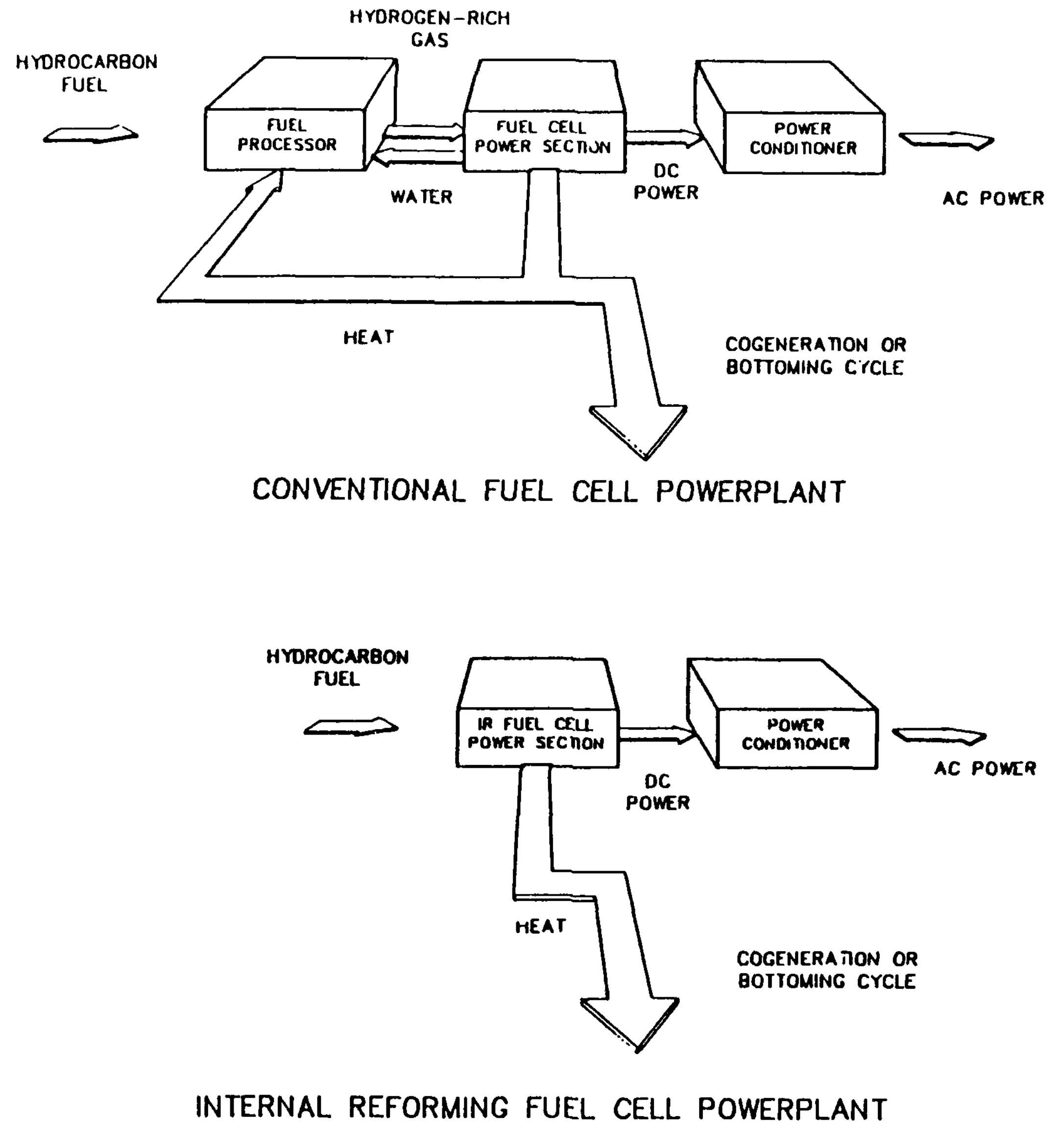


FIGURE F-3 Schematics of internal and external reforming fuel cell systems.

5 A/cm^2 at 0.8 V and 2 A/cm^2 at 1.0 V, and have a maximum continuous-rated power density of almost 7 kW/kg. Including the cooling system, controls and auxiliaries, they are capable of providing 3.3 kW/kg. This information was not available at the time of the most recent review (Bockris and Appleby, 1986). Conceptual SPE systems may be in the same class (for work up till 1985 see Appleby and Yeager, 1986). However, all the above will require cryogenic fuel and oxidant, and are only capable of specialized application. By way of contrast to the above, the 90 kg space-shuttle unit, representing 1975 technology, produced 12 kW nominal, and the 115 kg Apollo unit (1965 technology) produced 1.4 kW.

Atmospheric pressure SPE units operating on hydrogen may be now capable of 0.3 A/cm^2 at 0.6V, and unlike PAFC units, they can produce power from a cold start. They are capable of 0.7 kW/kg, and should therefore be of use in man-portable units if a source of hydrogen is available. Hydrogen in lightweight cylinders or advanced reversible hydrides would weigh about 2 kg/kWh, whereas Kipp-type generators using lithium hydride/water would weigh less than 1 kg/kWh.

PAFCs currently weigh about 5 kg/m^2 for the stack components and 2 kg/m^2 for the electrolyte (Appleby, 1986). Based on state-of-the-art atmospheric pressure performance, this represents about 0.17 kW/kg. Hence, the active components of a 40 kW stack would weigh 235 kg. However, peripherals, including coolers, the container, and endplates will increase this substantially. Early 1980s 40 kW stacks, operating at a lower power density, weighed about 300 kg (active components), 680 kg being the total weight. The fuel processor and controls bring this to 3,600 kg. Future units, with advanced fuel processors capable of handling JP-8 fuel might weigh 1,800 kg for 40 kW, and be capable of 30 percent or greater efficiency. The PAFC stack technology is mature (even though capable of further development), and the major research emphasis required to make use of the unique tactical characteristics of small JP-8 fuel cell units (extremely low acoustic and infrared (IR) signature) is on fuel processing to efficiently convert JP-8 to hydrogen-rich gas.

The MCFC has a stack weight about twice that of the PAFC, thus is unlikely to be a contender for MEP applications. However, the small monolithic SOFC may conceptually be able to handle JP-8 fuel with internal reforming, for a stack weight (projected) of 5 kW/kg. System size, including heat-exchangers, cannot be presently predicted, but it can be much less than that for the PAFC. However, IR signature would require careful attention. This area requires future research and development.

APPENDIX G

BATTERIES

A battery consists of a number of galvanic cells. A primary cell converts chemical energy directly into electric energy and consists of two electrodes of dissimilar material isolated from each other in a common ionically conductive electrolyte, either liquid or solid. A secondary, or rechargeable, cell can allow electric energy to be input, converted to chemical energy, and thus stored.

The Army currently uses small primary and secondary batteries for utility purposes (e.g., flashlights), and for electronic equipment, whereas larger secondary batteries of the standard lead-acid type are used for starting internal combustion engines and for auxiliary power supply for vehicles. Only small primary and secondary batteries will be considered here.

Especially with regard to man-portable uses, important characteristics of small Army batteries are light weight and volume, that is, high energy density, good shelf-life characteristics, and reasonable cost. Cycle life (for secondary batteries) is of lesser importance. Present small batteries include alkaline primary cells, nickel-cadmium (Ni-Cd) and lead-acid secondary cells, and lithium primary cells. In 1984, lithium/sulfur dioxide (Li/SO_2) replaced the magnesium/manganese dioxide (Mg/MnO_2) primary system, and has a much better low-temperature performance and higher energy density, important reasons for its development (Table 4-2).

The Army hopes that the future system will standardize around rechargeable lithium batteries in the form of the "universal field battery" proposed for the 1995 time-frame (Gilman, 1987). This battery will be either throwaway or rechargeable, depending on circumstances (training or warfare conditions). Before the introduction of the universal field battery, it is expected that the lithium/sulfur oxychloride ($Li/SOCl_2$) throwaway unit will continue to be used for high-power applications, the present generation of rechargeable lithium cells (which are of modest power density) gradually replacing Ni-Cd cells.

As an example of the need for a universal lithium battery, 473 different types of batteries were previously in the inventory, of which 192 have been removed. Twelve batteries support 112 end-item applications, one of which can be used for 48 end-items (Berger, 1987).

Lithium batteries can satisfy the high current requirements in new devices coming into the inventory, and are vital for meeting low-temperature requirements, giving all-weather capability. In addition, the substantial weight and volume reduction compared with Mg/MnO_2 and Ni-Cd can result in a lower cost per watt-hr (Wh) or per Wh per cycle for secondary cells.

Lithium batteries were developed in the early 1970s, were first tested at Fort Bragg in 1975, and were introduced in Alaska in 1977. Since that time 10 battery types have been fielded. Procurement started at 41,356 batteries in 1979, rising to over two million in 1985. There are some safety questions asked about lithium batteries: explosive incidents have occurred with large Air Force lithium/thionyl chloride ($Li/SOCl_2$) batteries, and for consumer uses the AA size is the largest lithium battery offered for distribution and sale. However, the Army is very satisfied with its safety record (0.0015 percent: 50 incidents out of 3,375,120 batteries fielded, compared with a commercial alkaline battery incident rate of 0.012 percent and 0.007 percent for commercial lead-acid batteries). All batteries now have non-corroding glass seals with contacts designed to prevent shorting of the spirally-wound structure. Pressure fill for SO_2 and $SOCl_2$ reagents is accurate, and strict reagent balance is maintained. Cell moisture is reduced to low levels. Finally, all cells are vented, and batteries are fitted with non-conducting cases, safety connections, and tamper-proof fuses.

Present lithium SO_2 and $SOCl_2$ battery problems include delay before voltage develops to the specified value, particularly at low temperature and after long-term storage. This results from the formation and redissolution of a passive film on the lithium surface. Another fundamental problem is the fact that discharge occurs at well below the open-circuit potential (OCV) at high current drains (e.g., at up to one volt below the OCV, which is acceptable in a battery developing up to three volts or more). The result is excessive heat generation inside the cell under these conditions, so that care is required in use. The only research and development (R & D) solutions to these problems are active cooling (which is not feasible in small batteries, and which will in any case seriously degrade energy density per unit mass and volume), or long-term electrochemical research on the fundamentals of discharge at lower overpotentials. Finally, the pressure relief valves currently used are considered to be unacceptable.

UNIVERSAL FIELD BATTERY R & D

R & D programs are currently in place to tackle the above issues, both at the Laboratory Command, LABCOM, Fort Monmouth, New Jersey and at the battery developers, all of whom are experiencing varying degrees of deficiency in their batteries. Intensive research is also being conducted on approaches to the universal field battery (Gilman, 1987).

Typical requirements for a "D" cell will be: Volume=49 cm^3, spirally-wound cathode area=400 cm^2, operating current density=1 to 5 mA/cm^2 for most requirements (that is, total current 0.4 to 2.0 A), with up to 20 mA/cm^2 for use with target designators (total current 8.0 A). Temperature range should be preferably -40°C to 71°C, -20°C to 54°C being essential. Storage requirement is less than 10 percent capacity loss during one month at 71°C, with less than 120 s of voltage delay (time to reach full power because of dissolution of the chemical film on the lithium negative). Safety requirements are no cell case rupture at short circuit, under forced discharge (reversal), under mechanical stress and in storage. Cost per amp-hr (Ah) per cycle for a training battery must be less than that for Ni-Cd, and for the universal battery it should be less than twice the Ah cost of that of a throwaway battery. Li/SO_2 and $Li/SOCl_2$ primary cells are now in use while lithium/sulfuryl chloride (Li/SO_2Cl_2) and calcium cells based on similar chemistry, are in the experimental stage (see Table G-1). Calcium (Ca) cells with both liquid cathode materials are less reactive than lithium systems and currently give less than their theoretical open circuit voltage OCVs. Lower reactivity, however, should eventually mean better storage capability and greater safety without sacrificing performance: $Ca/SOCl_2$ cells containing calcium tetrachloroaluminate ($Ca(AlCl_4)_2$) electrolyte with SO_2 additive to improve conductivity have about the same characteristics as those of Li/SO_2 cells. The greater safety of Ca cells should make them suitable for critical large-battery applications, but "overpassivation" presently occurs on storage, giving long delay times, and academic-industrial research on Ca coatings and electrolyte additives has been initiated to solve this problem.

At the present time, the universal field battery seems likely to be based on the use of rechargeable solid cathodes operating in the potential range where the solvent and electrolyte are electrochemically inactive. Presently, only SO_2 and organic solvents can be considered. The latter include ethers such as 2-methyl tetrahydrofuran, esters, and possibly dioxolane: sulfolanes are excluded because of poor low temperature performance. Research in new solvents is still required. The window of stability for SO_2 requires cathodes with standard potentials over 3 V positive to the lithium potential: the organic solvents can operate with cathodes having lower standard potential, but at the expense of energy density. A list of potential cathode materials for organic solvents is given in Table G-2.

Dissolved salts are, of course, required as electrolytes, but conductivities are, at best, still about two orders of magnitude below those of aqueous electrolytes and one order of magnitude less than those of SO_2-salt mixtures; thus, current densities are limited. The most effective salt used in organic electrolytes has been lithium hexafluoroarsenate(V) ($LiAsF_6$), but others (lithium hexafluorophosphate [$LiPF_6$]), lithium sulfone imides and similar compounds; see below) must be found if arsenic is considered to be an environmental hazard. Lithium perchlorate ($LiClO_4$) is effective, particularly in propylene carbonate, but causes an explosion hazard and has relatively poor low-temperature performance. For SO_2 only, lithium tetrachloroaluminate ($LiAlCl_4$) gives excellent results.

TABLE G-1 Open Circuit Voltages for Selected Primary Cells

Already Developed	Open Circuit Voltage (Volts)	Application
$LiSO_2$	2.95	Communications
$LiSOCl_2$	3.65 (high current)	GVS-5 laser designator
Experimental		
Li/SO_2Cl_2	3.91	
Calcium cells:		
$CaSOCl_2$	3.10	Provide better storage and safety in comparison to Lithium cells.
Ca/SO_2Cl_2	3.30	
Doped MnO_2	2.5	
Li_x/CoO_2	4.6	

TABLE G-2 Energy Parameters of Rechargeable Cathodes

Compound	Maximum Utilization (Mole Li/Mole) Material	Mid Discharge Cell Potential (V)	Specific Energy Quasi-theoretical Wh/Kg	(Wh/lb)
TiS_2	1.0	2.1	480	(217)
MoS_2	1.0	1.8	303	(138)
$Cr_{0.5}V_{0.5}S_2$	1.0	2.3	502	(228)
MoO_3	1.5	2.2	508	(231)
V_2O_5	1.0	3.1	457	(208)
V_6O_{13}	6.0	2.2	636	(289)
a-V_2O_5	2.0	2.5	714	(325)
MoS_3 (Amorphous)	3.0	1.9	720	(327)
A-CR_3O_8	1.0	2.7	1078	(490)
CoO_2	1.0	3.9	1046	(475)
SO_2	2	3.0	1111	(505)
Polyacetylene	0.06	3.5	209	(95)

Typical energy densities for training, limited rechargeability (throwaway) and universal field batteries, are given in Table 4-2. All should have excellent storage characteristics and should be made from inexpensive materials. Transition metal oxide lithium intercalation cathodes associated with ester electrolytes (methyl formate and acetate) with $LiAsF_6$ are presently preferred over the corresponding sulfides, phosphosulfides or selenides. These cathodes will include V_6O_{13}, $V_9Mo_6O_{40}$ and variants doped by phosphorus. Doped MnO_2 and Li_x/CoO_2 show considerable promise, but the latter requires more stable solvents than those currently available.

The alternative (at present) is a rechargeable SO_2-based system. First efforts on such systems were made by Duracell using the primary battery electrolyte (acetonitrile containing SO_2 and lithium bromide [LiBr]) with a carbon cathode. This showed poor rechargeability at both electrodes. The use of SO_2 alone as solvent, using high-cost Li chlorochlosoborane salts did provide lithium rechargeability but not very good carbon cathode performance (using the reaction: $2SO_2 + 2e^- = S_2O_4^=$).

This work was conducted by both Duracell and General Telephone and Electronics (GTE). Duracell showed that when SO_2 is used with $LiAlCl_4$ and a solid redox cathode that functions inside the window of stability of SO_2 (such as copper chloride [$Cu_2Cl_2/CuCl_2$]), rechargeability is good, but storage capacity is insufficient. Finally, Duracell's use of a new carbon cathode formulation yielding a surface product of apparent formula $LiCl\text{-}Al(OSO\text{---}C)_3$ also yields a rechargeable system of capacity limited by carbon surface area, typically about half of the primary cell.

Major problems in this system are, therefore, low discharge capacity, together with formation of dendritic lithium electrodeposits on charge and chemical instability of available separator materials. R & D approaches to improve the cell include surface and morphological modification of the cathode to catalyze SO_2 reduction or modify the reduction products, or both; to use reactants other than $CuCl_2$ and SO_2; to use coatings on the lithium anode to give improved storage and cycle life; to use improved electrolytes consisting of new salts and new salt mixtures, for example, organic or inorganic cosolvents or additives; and to use improved separators.

Enough chemical variations would seem to exist to allow the development of a successful universal field battery within the 1995 time-frame, in time for Army 21 mission concepts (Higgins et al., 1987; see Table G-3 for requirements). Note that batteries do not necessarily fulfill all the requirements for the missions listed: other power sources may be more appropriate, particularly specialized fuel cells or batteries connected to supercapacitors for high pulse power applications.

Supercapacitors are electrolytic condensors that operate using the Faradaic capacitance of an electrochemical reaction taking place in a monolayer of surface of each electrode. For example, for the formation of a monolayer of absorbed oxide on platinum, this may represent 500 microcoulombs/cm^2, compared with about 20 microcoulombs/cm^2 for the Hemholtz double layer capacitance used in conventional electrolytic oxide-film capacitors (Raistrick et al., 1987). Since they involve a monolayer electrochemical process taking place between charge and

TABLE G-3 Electrical Requirements for Various Missions

Requirements	C^3I[a]	Adv. C^3I	Robotics	Weapons (Direct)	Battery	Capacitor
Voltage	< 20V	< 20V	50-100V	1000	1000V	1000V
Current Density	2-5 mA/cm^2	20 mA/cm^2	0.1 A/cm^2	100 A/cm^2	< 0.1 A/cm^2	100 A/cm^2
Weight	< 2 lbs.	< 2 lbs.	100 lbs.	2000 lbs.	1800 lbs.	200 lbs.

[a] Command Control Communications Intelligence

discharge, they may be regarded as aqueous batteries with very thin plates of extremely high specific surface area, which deliver low energy density (about 2 Wh/kg), but have very high pulse power capability.

A "refuelable" metal-air battery could be another possibility although it can be considered a form of a fuel cell. The most efficient and certainly the safest system would be aluminum-air, for which the overall reaction is:

$$2Al + 3/2O_2 + 3H_2O = 2Al(OH)_3$$

Counting only aluminum and water as consumables, the equivalent energy density of aluminum-water "cartridges" would be about 2,230 Wh/kg, at an average cell potential of 1.5 V. However, this would be degraded by perhaps 30 percent because of the effect of parasitic side-reactions, and the system would have the disadvantage of requiring refueling of individual cells in the battery, each containing a potentially hazardous caustic electrolyte. This disadvantage can probably be eliminated by good design, and the system is worth further investigation. A more complex version of this battery for use in electric vehicles is currently being developed by the U.S. Department of Energy (Salisbury and Behrin, 1980).

SUMMARY

Use of batteries in the Army includes communication equipment, night sights, radar, position-location reporting systems, and thermal viewers. Future uses include laser rangefinders and target designators, mini-bolt lasers, thermal weapon sights, chemical agent sensors and alarms, and heated handwear (see Table G-4 for requirements for laser designator and rangefinder). The Army's battery R & D policy seems sound, since it allows for a good deal of development redundancy. However, the Army does not currently perceive a need for small portable to semiportable power sources between the class currently producing several watts continuous power (with higher pulse power ratings), intended to be served by the universal field battery, and small JP-8 fueled generators in the 3 kW class. The committee's perception is that this is a gap that is likely to narrow in the future as new individual energy-intensive electronic devices or directed-energy weapons are conceived and deployed. This seems to be an inevitable development as such devices become more cost-effective. Furthermore, for man-portable missions, batteries have virtually zero noise and infrared signature.

Depending on the mission requirement, advanced batteries may be able to fill some of this gap, but the energy density of even the most optimistic battery system is only about 400 Wh/kg, compared with a pseudo-practical value of 3,700 Wh/kg for diesel fuel (assuming conversion at 25 percent efficiency in a diesel or Stirling heat engine). The most important parameter for a man-portable power source is its total weight for a mission of given duration, that is,

$$\begin{aligned}\text{Total weight} &= \text{Energy Source Weight} + \text{Power System Weight}\\ &= (kg/Wh) \times (W) \times (\text{duration, in hours}) + (kg/W) \times (W)\\ &= (W)\,[(kg/Wh)\,(hours) + (kg/W)]\end{aligned}$$

For example, a throwaway battery with a 400 Wh/Kg energy density for a 12-hour mission requirement in the context of a 1 kW system, would weigh

TABLE G-4 Use Parameters for Different Equipment with Lithium and Mg/MnO_2 Batteries

Lithium Batteries	AB/TVO-2 Ground Laser Designator	AN/GVS-5 Laser Range Finder
Time of Use at -31.7°C (-25°F)	34 min	--
Time of Use at 21°C (70°F)	114 min	
Number of Rangings at 21°C (70°F)	--	11,300
Number of Rangings at -29°C (-20°F	--	8,200
Mg/MnO_2 Batteries		
Time of Use at -17.8°C (0°F)	2 min	--
Time of Use at 21°C (70°F)	15 min	--
Number of Rangings at 21°C (70°F)		800
Number of Rangings at -29°C (-20°F)		0

30 kg ([1000/400] x 12), since the power system weight in a conventional battery is already included in the energy source weight, which assumes a complete discharge of the battery in one hour. In fact, a battery capable of giving 2.5 kg/kWh (400 Wh/kg) can normally produce peak power levels very much in excess of this nominal one-hour rating. Batteries have the advantage of not needing a separate fuel supply, such as a diesel engine needs, and an output of dc power that can be directly supplied to an electronic device incorporating its own power-conditioning system.

An alternative to a rechargeable or throwaway battery system would be a small fuel cell (see section on Fuel Cells in Chapter 4 and Appendix F), or a metal-air battery (itself a form of fuel cell) equipped with a dissolving metal anode.

It is clear from the above discussion that there are developments and applications of an advanced battery, suitable for man-portable missions. As can be noted from other discussions, their use will also depend on signature constraints and on the mission requirement: that is, the number of hours of autonomy envisaged before refueling. The trade-off here is between the peak W/kg capability of the power source, which depends on the power requirement of the mission, compared with the energy stored (in kilowatt-hours) per mean kilowatt (that is, the mission time in hours). The peak power requirements may be best served by a hybrid system (e.g., a power-source battery or supercapacitor combination). This will be particularly important in the small portable power units that can be envisaged in the Army 21 context (Higgins et al., 1987; see Chapter 5).

APPENDIX H

VEHICLE ENGINE NOISE

Some noise analysis has been conducted for the General Motors (GM) High Mobility Multipurpose Wheeled Vehicle (HMMWV). The HMMWV is powered by a GM 6.2 liter, naturally-aspirated V8 indirect-injection, diesel engine, producing 160 brake-hp (120 kW) at 3,600 rpm. HMMWV noise data were obtained with the vehicle stationary, and the engine operating at fixed speed, simulating a power generating "mission". Results were compared with the typical nondetectability limit of 300 m (observer distance) / 10 m (measurement distance).

Full load (60 kW) operation at 1,700 rpm, with the cooling fan on, produced a noise level of 77.6 dB(A), substantially exceeding the typical nondetectability limit at both low frequencies (10 dB at 100 Hz) and at high frequency (20 dB at 2.5 to 5 KHz; Figure H-1).

Since the vehicle's torque converter would not permit full-load engine operation above 1,700 rpm, additional tests were conducted under no load conditions. With the cooling fan removed, noise levels of 71.5 dB(A) and 81.6 dB(A) were measured at 1,800 and 3,600 rpm, respectively (Figure H-2). Thus, doubling engine speed increased acoustical energy by a factor of five. Frequency content in excess of the typical nondetectability limit broadened at 3,600 rpm, probably because of higher engine noise.

Tests at 1,800 and 3,600 rpm, no load, with the cooling fan operating, produced startling results. Fan operation increased vehicle noise 5.5 dB(A) at 1,800 rpm. At 3,600 rpm, the cooling fan increased vehicle noise nearly 10 dB(A). Clearly, the fan is a major source of noise, particularly at high speed.

The fan noise source spectrum can be determined by taking the logarithmic difference between the "fan on" and "fan-off" conditions at a given engine speed. At 1,800 rpm, the cooling fan noise spectrum features a 315 Hz resonance, likely caused by blade passage frequency, a typical characteristic of the HMMWV's evenly spaced fan blade design. At 3,600 rpm, excessive fan noise occurs primarily from 630 Hz to 6 KHz. This noise is probably from blade vortex shedding, an interaction of the trailing edge of the blade with instability waves occuring in the laminar boundary layer.

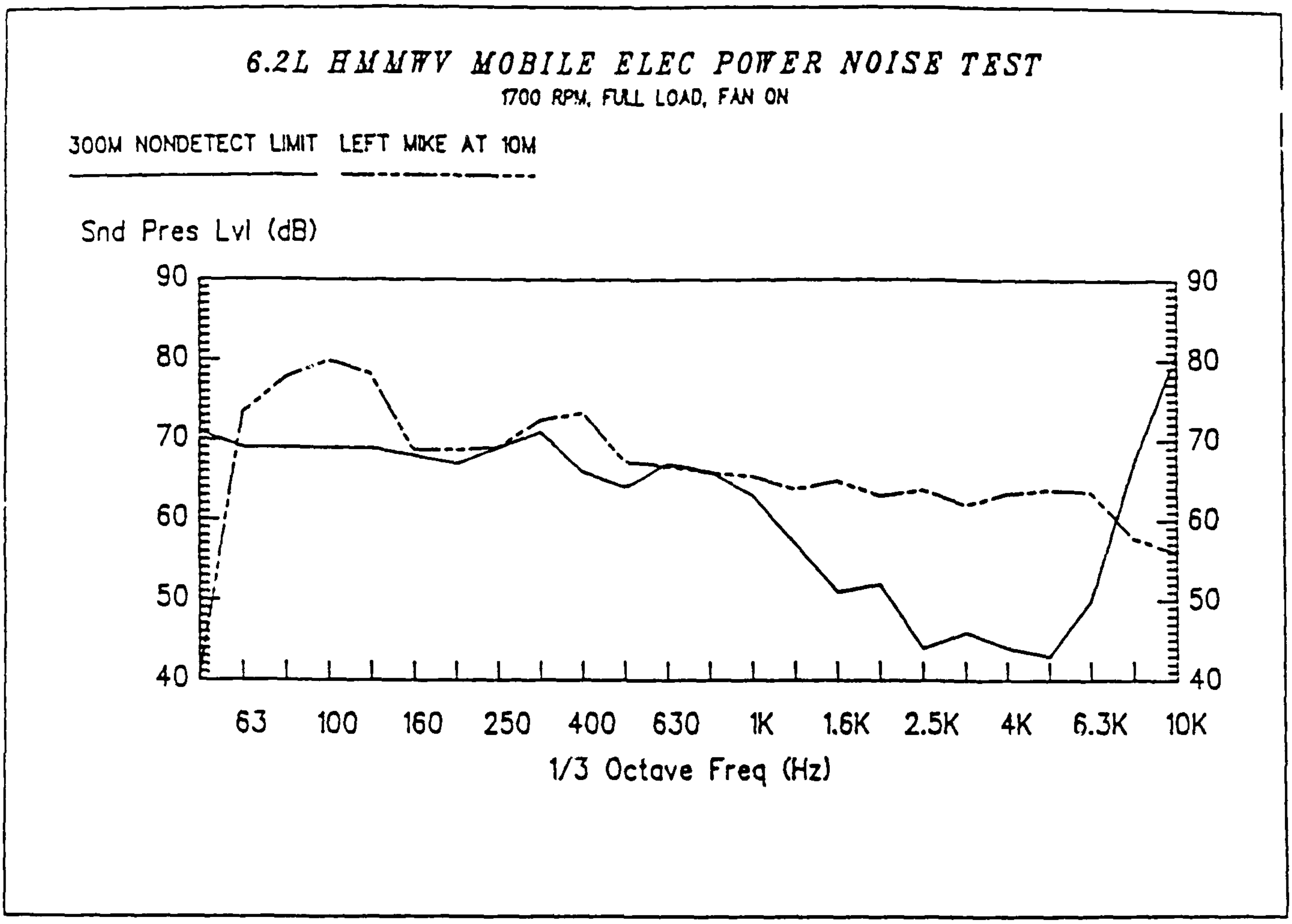


FIGURE H-1 6.2 L HMMWV mobile electric power noise test.

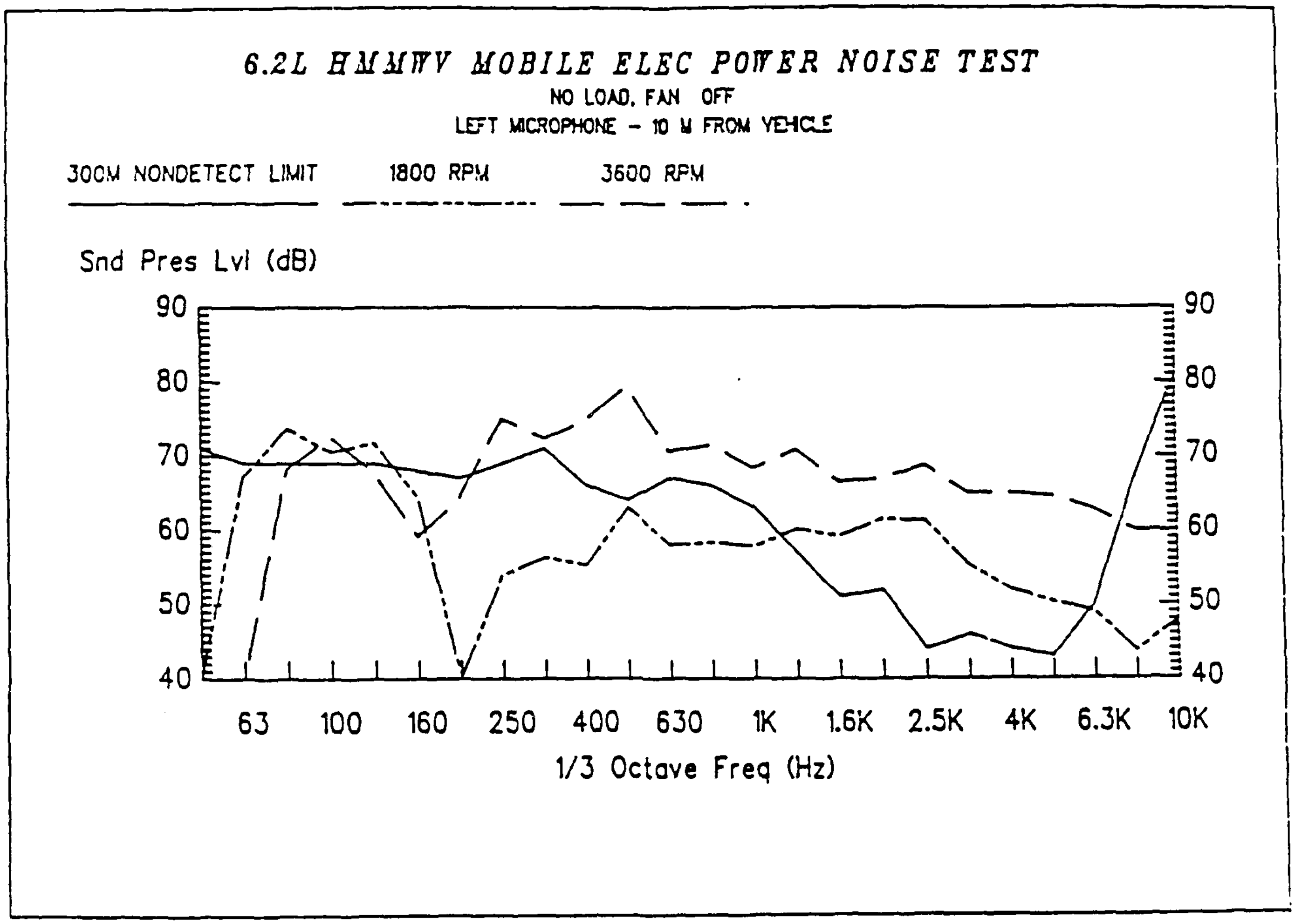


FIGURE H-2 6.2 liter HMMWV mobile electric power noise test.

At 1,500 rpm with no load, with the fan on, the vehicle noise level was 73.1 dB(A); 4 dB(A) less than at 1,800 rpm, and 18 dB(A) less than at 3,600 rpm. Although limiting generator capacity, operation at lower engine speeds would reduce effort needed to comply with the typical nondetectability limit.

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